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THESIS

AN INTERACTIVE CODE FOR A PRESSURIZED WATER REACTOR
INCORPORATING TEMPERATURE AND XENON FEEDBACK

by

Gregory Garver Heath

June 1980

Thesis Advisor: P. J. Marto

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post-shutdown Xenon transient response was also modeled. The interactive program was coded in FORTRAN-IV language, and the simulation program was coded in IBM CSMP-III language.

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An Interactive Code for a
Pressurized Water Reactor
Incorporating
Temperature and Xenon Feedback

by

Gregory Garver Heath
Lieutenant Commander, United States Navy
B.S.M.E., United States Naval Academy, 1971

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ENGINEERING SCIENCE

from the

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ABSTRACT

An interactive computer model of a highly enriched pressurized water reactor was developed, using the applicable plant parameters from the Shippingport Atomic Power Station. The point reactor kinetics equations for one delayed neutron precursor group were linearized using small perturbation theory. The model included both moderator and Xenon-135 reactivity feedback effects, as well as an automatic reactor protection and average reactor coolant temperature control system. The thermal response of the model plant was simulated for normal operating transients induced either by control rod or turbine load changes. The post shutdown Xenon transient response was also modeled. The interactive program was coded in FORTRAN-IV language, and the simulation program was coded in IBM CSMP-III language.

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I. INTRODUCTION

Computers have been used in the design and analysis of nuclear reactors since the inception of reactor technology, and many codes have been developed. More recently, digital computer programs have been used as learning devices for nuclear engineering students. The formulation of the computational problem of predicting the behavior of a nuclear reactor has been greatly facilitated with the use of high level computer languages.

The purpose of this work was to develop a computer assisted learning device to be used by students taking nuclear engineering courses at the Naval Postgraduate School. The program graphically displays the simulated kinetic and thermal transient responses of a pressurized water reactor power plant. The reactivity feedback effects of Xenon-135 poisoning and moderator temperature are incorporated into the model. Normal operating transients, starting from a steady state critical condition, can be induced by ramp changes in either control rod position or turbine load. The initial reactor power level and reactivity change mechanism are chosen by the program user. For user convenience, these inputs are prompted and entered interactively, after which the simulation is run with no further user action required.

A pressurized water reactor (PWR) was modeled as it is the most common type of reactor used for power plant application. As a realistic reference, the model design incorporated the applicable characteristics of the Shippingport Atomic Power Station, whose nuclear parameters were the most compatible, of available PWR core data, with the assumption of a highly enriched core made in the model design.

The model was developed by treating the reactor kinetics and other plant component thermodynamic relationships as transfer functions [1]. The point reactor kinetics equations were linearized using a Taylor expansion or small perturbation technique [2]. This same perturbation technique and lumped parameter analysis were applied to the plant's linear differential heat transfer and Xenon-135 equations [3]. The individual transfer functions were then integrated into an overall plant block diagram. The program also features a reactor protection and average reactor coolant temperature control scheme.

IBM CSMP-III language was chosen to formulate the model simulation as it has inherent routines to invert the transfer functions to the time domain.

II. MODEL DESIGN CONSIDERATIONS

Lumped parameter analysis and first order perturbation theory were used throughout the model development. All the nuclear variables which were used in the reactor kinetics and Xenon-135 decay equations were considered to be averaged values of the variables over the neutron energy spectrum. Similarly, the thermodynamic variables which were used in the plant's heat transfer equations were considered to be averaged values over the volume of the particular component.

Because of these approximations and other assumptions made in the model development, the simulation should not be considered a design or stability analysis. Instead, the simulation shows the model's large scale reactor kinetic and thermal trends during normal operating transients.

For similar reasons, although certain plant parameters of the Shippingport Atomic Power Station were incorporated into the model, the simulation cannot be considered to reflect the operating characteristics of this power plant. The Shippingport core is a seed and blanket type whereas the model core is a uniform mixture of highly enriched fuel and support materials.

A. PRESSURIZED WATER REACTOR

The pressurized water reactor (PWR) is the most widely used reactor type in central power plant applications and the only type currently used in naval propulsion.

A simplified schematic of the modeled PWR plant is shown in Figure 1. The modeled reactor contains a highly enriched core which is light

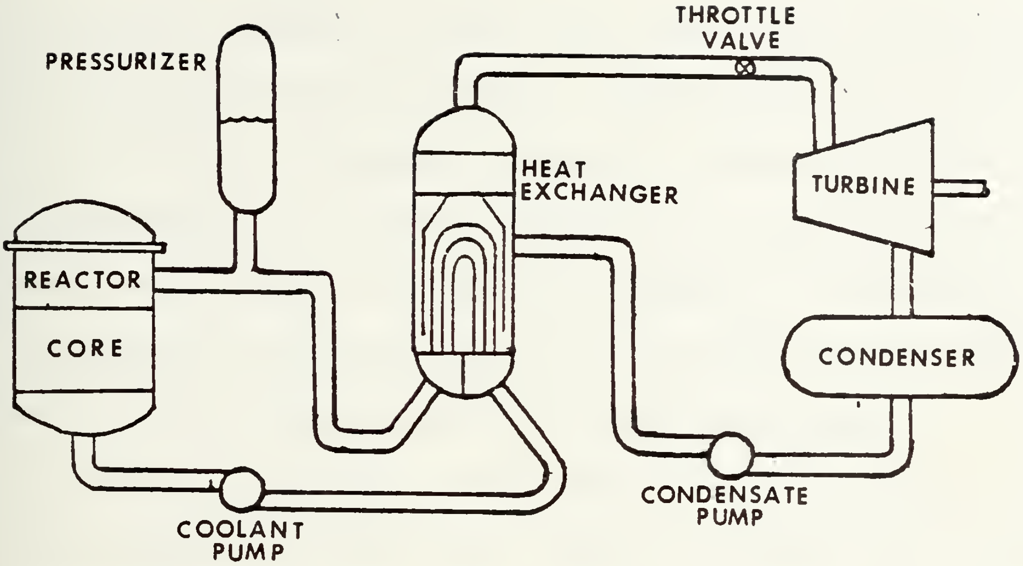


Figure 1. Schematic of the Model Plant

water moderated and cooled. The modeled plant contains two closed loop thermodynamic systems coupled by a heat exchanger.

In the primary system, heat generated from thermal fission is transferred to the coolant as it passes through the reactor, raising the coolant's temperature. The high temperature coolant leaving the reactor is circulated by a pump through tubes inside of a heat exchanger where it gives up some heat to a secondary fluid. A pressurizer maintains the primary coolant at a sufficiently high pressure so that the bulk temperature of the coolant is kept below the saturation temperature.

On the secondary side of the heat exchanger, the temperature of the entering feedwater is raised to the boiling point and saturated steam is produced. The steam is delivered to a turbine, is condensed and returned to the heat exchanger, completing the second closed loop.

B. MODEL AND PROGRAM FLEXIBILITY

The model was designed to simulate only normal operating transients from an initial steady state condition. Reactor accidents and startup were not considered in the model development. However, the model's reactor control module will simulate either a full or constant insertion of control rods if certain parameters are exceeded. This feature was not incorporated for accident analysis, but to keep parameters within the limits of the assumptions made in the model development.

The applicable Shippingport plant characteristics are fixed in the simulation program. User inputs are limited to choosing initial power level, from which other initial parameters are adjusted, and the plant perturbation mechanism, either control rod movement or turbine load change. These perturbations occur at fixed rates which limit the amount of reactivity that can be inserted during the simulation.

Originally it was envisioned that an overall program would feature not only interactive input capability but also produce real time graphical displays of the transient for a user at a time sharing computer terminal which had graphics capability. However, the computer language (IBM CSMP-III) required to solve the model's algorithms was not available on the time sharing system, and furthermore, the programs long execution time precluded any real time response.

In order to still provide as much user facility as possible with these restrictions, the interactive feature was partially retained for data input. Using a computer language available on the time sharing system (FORTRAN-IV), a program which interactively prompts the user to

enter specified controlling parameters was developed. This program incorporates logic routines which permit inputs only within requested ranges. This feature allows for data reentry if a user error is made, and ensures that only inputs compatible with the model development's assumptions are used in the simulation.

After the input is completed, the initial transient conditions are displayed at the terminal. A separate internal control program then transfers the user supplied inputs into the simulation program. The control program then transfers the simulation program to the batch processing system for execution. The interactive program notifies the user that this has been done. Hard copy plots of the transient are subsequently produced. The post-shutdown Xenon behavior module is located in the interactive program and produces real time graphical displays at the terminal.

Thus there are three distinct programs:

1. An interactive program to prompt and receive user input, and also simulate post-shutdown Xenon behavior.
2. A batch processed program which simulates the transient response to the user inputs.
3. An internal control program which interfaces these two programs.

III. MODEL DEVELOPMENT

A. POINT REACTOR KINETICS EQUATIONS

A lengthly and formal derivation of the point kinetics equations is found in Reference 4 and will not be repeated here. More generally these equations are obtained from one group neutron diffusion theory with the assumption that the neutron flux is deparable in time and space, and with the inclusion of delayed neutrons [5]. They are listed below.

$$\frac{d\phi(t)}{dt} = \frac{\rho(t)-\bar{\beta}}{\Lambda}\phi(t) + \sum_i \lambda_i C_i(t) + Q(t) \qquad (1)$$

$$\frac{dC_i(t)}{dt} = \frac{\bar{\beta}_i}{\Lambda}\phi(t) - \lambda_i C_i(t) \quad i = 1,2,\ldots \qquad (2)$$

where $\phi(t)$ = Flux amplitude function

$\rho(t)$ = Reactivity

$C_i(t)$ = Effective concentration of the ith delayed neutron precursor group

$Q(t)$ = Extraneous delayed neutron source strength

$\bar{\beta}_i$ = Effective delayed neutron fraction from the ith group

λ_i = Decay constant of the ith group

and $\bar{\beta} = \sum_i \bar{\beta}_i$ = Total effective delayed neutron fraction

These equations are referred to as the point reactor kinetics equations not because the reactor is considered as a single point in their application, but since spatial variations are neglected. $\bar{\beta}_i$, Λ, and λ_i are assumed to be constant.

If the neutron flux spatial variation is assumed to be time invariant, $\phi(t)$ can be considered to represent the number of neutrons in the

core. Equation (1) may then be seen as a neutron rate equation where the three terms on the right hand side represent the rate of production of prompt, delayed, and source neutrons respectively.

Equation (2) is a rate equation for the ith delayed neutron precursor group. The two terms on the right hand side represent production and decay rates respectively. The precursors are comprised of approximately thirty isotopes which historically have been divided into six groups with decay constants ranging from 0.0124 to 3.0 seconds $^{-1}$ for ^{235}U. In the model, the precursors were considered to be represented by one effective group characterized by an averaged decay constant [2].

$$\lambda = \left[\frac{1}{\bar{\beta}} \sum_{i=1}^{6} \frac{\bar{\beta}_i}{\lambda_i} \right]^{-1}$$

and an effective delayed neutron fraction

$$\bar{\beta} = \sum_{i=1}^{6} \bar{\beta}_i$$

In equations (1) and (2), reactor power may be substituted for neutron flux if the precursor concentration is modified by $C = E_f \Sigma_f C_{old}$ since

$$P = E_f \Sigma_f \emptyset$$

where P = Reactor power
E_f = Energy released per fission
Σ_f = Macroscopic fission cross section
$\emptyset$ = Integrated one group neutron flux

For a reactor operating at power, the source term contribution to the overall neutron population is negligible, i.e., $Q \approx 0$.

Incorporating these assumptions, equations (1) and (2) reduce to:

$$\frac{dP(t)}{dt} = \frac{\rho(t) - \bar{\beta}}{\Lambda} P(t) + \lambda C(t) \qquad (3)$$

$$\frac{dC(t)}{dt} = \frac{\bar{\beta}}{\Lambda} P(t) - \lambda C(t) \qquad (4)$$

1. Zero Power Reactor Transfer Function

Consider an initially critical steady state reactor at some power level P_0 at $t \leq 0$. Equations (3) and (4) each yield:

$$C_0 = \frac{\bar{\beta}}{\lambda\Lambda} P_0 \qquad (5)$$

$$\begin{aligned} \text{Now let } P(t) &= P_0 + \delta P(t) \\ C(t) &= C_0 + \delta C(t) \\ \rho(t) &= \rho_0 + \delta\rho(t) \end{aligned} \qquad (6)$$

where the zero subscript denotes the initial steady state value and the delta prefix a small perturbation imposed at t = 0 about this value.

Noting that $\rho_0 = 0$ for a critical reactor and substituting equations (5) and (6) into equations (3) and (4) yields for $t \geq 0$

$$\frac{d}{dt} \delta P(t) = \frac{Po}{\Lambda} \delta\rho(t) - \frac{\bar{\beta}}{\Lambda} P(t) + \lambda \delta C(t) \qquad (7)$$

$$\frac{d}{dt} \delta C(t) = \frac{\bar{\beta}}{\Lambda} \delta P(t) - \lambda \delta C(t) \qquad (8)$$

where the $\frac{\delta P \delta\rho}{\Lambda}$ term in equation (7) has been neglected.

Taking the Laplace transforms of equations (7) and (8):

$$s\, \delta P(s) = \frac{P_o}{\Lambda} \delta\rho(s) - \frac{\bar{\beta}}{\Lambda} \delta P(s) + \lambda \delta C(s) \qquad (9)$$

$$\delta C(s) = \frac{\bar{\beta}}{\Lambda} \delta P(s) - \lambda \delta C(s) \qquad (10)$$

Solving equation (10) for C(s), substituting this into equation (9), and rearranging, yields:

$$\frac{\delta P(s)}{\delta \rho(s)} = \frac{P_o}{s\left(\Lambda + \frac{\beta}{s+\lambda}\right)} \tag{11}$$

This is the zero power reactor transfer function, so called because the reactor is assumed to be operating at a sufficiently low enough power that no feedback effects are realized. These effects are examined in the following sections.

Equation (11) may be represented in block diagram form as shown in Figure 2.

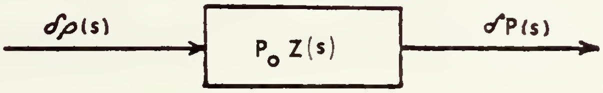


Figure 2. Block Diagram of the Zero Power Reactor Transfer Function

where $Z(s) = \frac{1}{s\left(\Lambda + \frac{\beta}{s+\lambda}\right)}$

2. Limitations of the Point Reactor Kinetics Equations

The point reactor kinetics equations derivation is based on the assumption that the spatial dependence of the neutron flux is negligible. This assumption limits the validity of these equations to transients where this remains a reasonable approximation such as those which result in only small changes in reactivity. The small perturbation technique used in the development of the zero power reactor

transfer function also requires only small changes in reactivity if the first order approximation is to hold. Specifically, ρ must be less than $0.5\bar{\beta}$. Physically, when ρ is greater than $\bar{\beta}$ the reactor is critical on prompt neutons alone. The simulated transients imposed on the model were limited to ensure that excessive amounts of reactivity were not introduced.

B. REACTIVITY FEEDBACK MECHANISMS

In the zero power reactor point reactor, the power level is assumed to be so low that it does not affect the reactivity, thus there are no feedback effects. However, for a reactor operating at a useful power level, feedback effects do exist and the reactivity becomes an implicit function of the reactor power level (or neutron flux). This dependence arises since reactivity depends on macroscopic cross sections which involve the atomic number densities of material in the core:

$$\Sigma = N\sigma$$

where Σ = Macroscopic cross section (cm^{-1})
N = Atomic number density ($atoms/cm^{3}$)
σ = Microscopic cross section (cm^{2})

The atomic number density can depend upon the reactor power level since the concentrations of certain nuclei are constantly changing due to neutron interactions. Material densities also depend upon temperature which is a function of reactor power level and hence the flux.[1]

---

[1] Duderstadt, J. J. and Hamilton, L. J., Nuclear Reactor Analysis, 1st ed., Wiley, 1976.

The two feedback mechanisms considered in the model were Xenon-let and moderator temperature.

Reactivity can also be changed directly by an external source such as control rods containing a neutron absorbing material. Thus the overall reactivity can be written as:

$$\delta\rho = \delta\rho_E + \delta\rho_X + \delta\rho_T \qquad (12)$$

where $\delta\rho_X = F_X\ P$

$\delta\rho_T = F_T\ P$

$\delta\rho$ = Overall core reactivity

$\delta\rho_E$ = Externally added reactivity

$\delta\rho_X$ = Xenon-135 feedback reactivity

$\delta\rho_T$ = Moderator temperature feedback reactivity

Fx = Xeonon transfer function

F_T = Moderator temperature transfer function

Equation (12) with the previously developed zero power reactor transfer function, given by equation (11), are incorporated in the block diagram below:

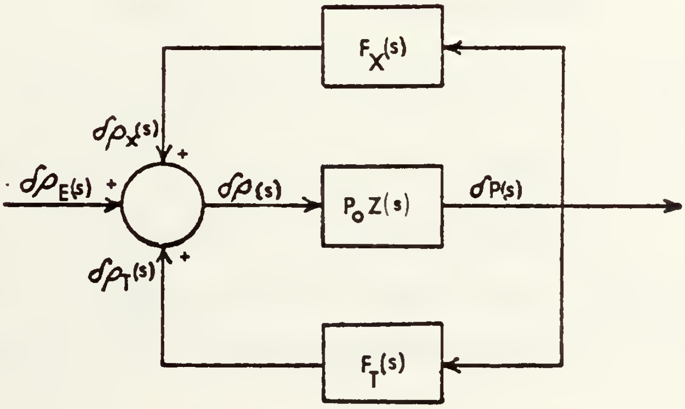


Figure 3. Block Diagram of the Reactor Transfer Function with Xenon-135 and Moderator Temperature Feedback Loops, and External Reactivity

The next step in the model development was to derive the Xenon-135 and moderator temperature transfer functions.

1. Xenon-135 Transfer Function

Xenon-135 is the most significant fission product poidon because of its enormous thermal neutron absorption cross section and relatively large fission yield. This isotope is not only produced directly from fission but also from the decay of other fission products as shown in Figure 4.

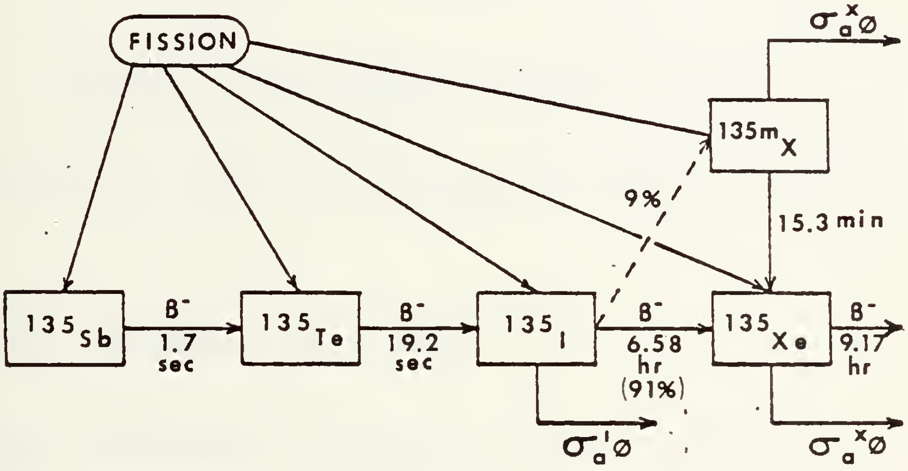


Figure 4. Xe-135 Decay Scheme

Since the β^- decay of Iodine-135 (^{135}I) and Xenon-135 (^{135}Xe), with the largest half-lives, are the controlling steps in this decay scheme, it was simplified by making the following assumptions:

1) All ^{135}I is produced directly from fission (the production of Antimony-135 (^{135}Sb) and subsequent decay to ^{135}I is considered instantaneous).

2) The short lived metastable ^{135m}Xe is ignored.

3) The removal of ^{135}I by neutron absorption is negligible for the neuton flux levels used in the model (10^{14} neutrons/cm^{2}sec).

4) All the ^{135}I decays to ^{135}Xe.

With these assumptions the effective decay scheme is shown in Figure 5.

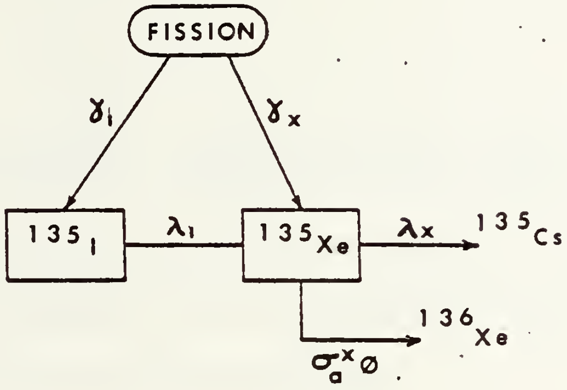


Figure 5. Simplified Xe-135 Decay Scheme

Using this decay scheme, the resulting rate equations for ^{135}I and ^{135}Xe are:

$$\frac{dI(t)}{dt} = \gamma_I \Sigma_f \phi(t) - \lambda_I I(t) \tag{13}$$

$$\frac{dX(t)}{dt} = \gamma_X \Sigma_f \phi(t) + \lambda_I I(t) - \lambda_X X(t) - \sigma_a^X \phi(t) X(t) \tag{14}$$

where I = ^{135}I number density (atoms/cm^3)

X = ^{135}Xe number density (atoms/cm^3)

Σ_f = Macroscopic fission cross section (cm^{-1})

ϕ = Integrated one group neutron flux (neutrons/cm^{2}sec)

γ_I = Effective ^{135}I fission yield

γ_X = Effective ^{135}Xe fission yield

λ_I = ^{135}I decay constant (sec^{-1})

λ_X = ^{135}Xe decay constant (sec^{-1})

σ_a^X = ^{135}Xe microscopic thermal neutron absorption cross section (cm^2)

Again, using the first order perturbation technique, let

$$I(t) = I_0 + \delta I(t)$$

$$X(t) = X_0 + \delta X(t) \qquad (15)$$

$$\phi(t) = \phi_0 + \delta\phi(t)$$

where the zero subscript denotes an initial steady state value and the delta prefix denotes a small perturbation about this value.

Upon substituting equations (15) into equations (13) and (14), and taking the Laplace transform, the relationship between the perturbation in ^{135}Xe and ϕ is derived (See Appendix A):

$$\frac{\delta X(s)}{\delta\phi(s)} = \frac{(\gamma_X \Sigma_f - \sigma_a^X X_0)s + \lambda_I(\gamma_I \Sigma_f + \gamma_X \Sigma_f - \sigma_a^X X_0)}{s^2 + (\sigma_a^X \phi_0 + \lambda_X + \lambda_I)s + \lambda_I(\sigma_a^X \phi_0 + \lambda_X)} = G_X(s) \qquad (16)$$

The change in reactivity caused by a small perturbation in ^{135}Xe concentration is also derived in Appendix A:

$$\frac{\delta\rho_X(s)}{\delta X(s)} = -\frac{1}{X_0 + \frac{\sigma_a^F}{\sigma_a^X} U} = \alpha_X \qquad (17)$$

where X_0 = Equilibrium ^{135}Xe number density before the perturbation (atoms/cm^3)

U = Uranium-235 (^{235}U) number density (atoms/cm^3)

σ_a^F = Microscopic thermal neutron absorption cross section of ^{235}U (cm^2)

A perturbation in neuton flux ($\delta\phi$) is directly proportional to a perturbation in reactor power (δP) as shown by:

where E_f = Energy released per fission

Σ_f = Macroscopic fission cross section of ^{235}U (cm^{-1})

or

$$\frac{\delta\phi(s)}{\delta P(s)} = \frac{1}{E_f \Sigma_f} = K \tag{18}$$

The product of equations (17), (16), and (18) yields:

$$\frac{\delta\rho_x(s)}{\delta X(s)} \frac{\delta X(s)}{\delta\phi(s)} \frac{\delta\phi(s)}{\delta P(s)} = \frac{\delta\rho_x(s)}{\delta P(s)} = \alpha_x G_x(s) K = F_x(s) \tag{19}$$

Equation (19) is the transfer function relating reactor power and ^{135}Xe feedback reactivity. This equation is shown in block diagram form in Figure 6 where it has been incorporated with the previously derived zero power transfer function given by equation (11).

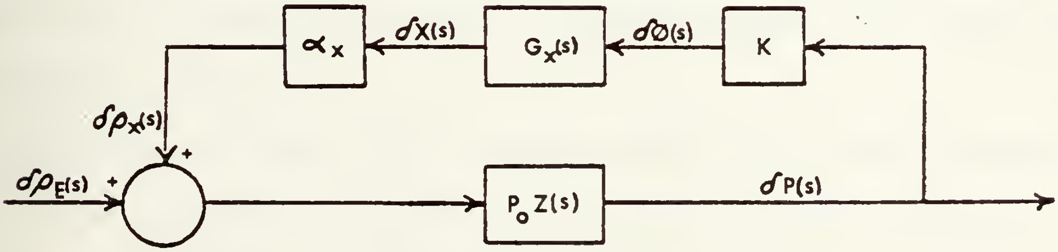


Figure 6. Block Diagram of the Reactor Transfer Function with Xenon-135 Feedback and External Reactivity

2. Moderator Temperature Feedback

Reactivity feedback from changes in moderator temperature occurs as a result of changes with moderator density. The density is also a

function of pressure, however, the pressure coefficient of reactivity is typically two orders of magnitude smaller than the temperature coefficient, and was therefore not considered in the model development. The moderator density affects the moderator number density and hence the macroscopic scattering cross section of the moderator.

The primary mechanism for the thermalization of the prompt and delayed neutrons is by elastic scattering interactions with the moderator nuclei. Hence, variations in the macroscopic scattering cross section will affect the rate at which neutrons become thermalized. Changes in the thermalization rate affect the fission rate, or reactor power level. Power level changes affect the moderator temperature, thus a feedback loop is created.

Because the moderator is also the coolant in the model, its temperature is not only a function of reactor power but also a function of the heat transfer process occurring in the heat exchanger, thus complicating the feedback loop.

Therefore, in order to develop this feedback mechanism analytically, it is first necessary to model the plant's heat transfer processes. This thermal analysis is done in the following section.

Another temperature feedback mechanism is the broadening of the Uranium-238 resonance absorption cross section for neutrons with increasing temperature. Because a highly enriched core was assumed in the model, with little Uranium-238, this effect was not considered.

C. THERMAL ANALYSIS

1. Reactor Heat Transfer Function

A lumped parameter model was assumed. This simplification provided a set of ordinary differential equation which were sufficiently accurate for the simulated normal operating transients. In the lumped parameter model, heat transfer in the reactor was assumed to occur at a single point. Thus, spatial variations were neglected. The core was considered to be a homogenized mixture of the uranium alloy fuel, the fuel cladding, and other structural materials, with a constant thermal capacity.

The equation for the heat flow from the core was obtained from a basic heat balance. The heat generated from fission equals the heat required to change the temperature of the core materials plus the heat transferred to the coolant. On a per unit time basis, the heat balance is:

$$P(t) = C_F \frac{dT_F(t)}{dt} + h_{FM} \left[T_F(t) - T_{AV}(t) \right] \qquad (20)$$

where $P(t)$ = Total Power generated in the core (Btu/sec)

$T_F(t)$= Average temperature of the core materials (°F)

$T_{AV}(t)$ = Average reactor coolant temperature (°F)

C_F = Total thermal capacity of the core materials (Btu/°F)

h_{FM} = Total heat transfer coefficient (Btu/° F sec)

A similar heat transfer balance must also hold for the heat being transferred to the coolant and transported out of the core. This heat is the last term of equation (20) and is transferred to the coolant as:

$$h_{FM}\left[T_F(t)-T_{AV}(t)\right] = C_M \frac{dT_{AV}(t)}{dt} + \dot{m}_m C\left[T_{H_o}(t)-T_{C_i}(t)\right] \qquad (21)$$

where C_M = Total thermal capacity of coolant in the core (Btu/°F)

$\dot{m}_m$ = Coolant mass flow rate (lbm/sec)

T_{H_o} = Average reactor coolant outlet temperature (°F)

T_{C_i} = Average reactor coolant inlet temperature (°F)

C = Specific heat of reactor coolant (Btu/lbm°F)

For simplification, the average reactor coolant temperature is assumed to be given by:

$$T_{AV}(t) = \left[T_{C_i}(t) + T_{H_o}(t)\right] / 2 \qquad (22)$$

Rearranging equation (20) yields:

$$T_F(t) + \tau_1 \frac{dT_F(t)}{dt} = T_{AV}(t) + \frac{\tau_1}{C_F} P(t) \qquad (23)$$

where $\tau_1 = \frac{C_F}{h_{FM}}$

Substituting equation (22) into equation (21) to eliminate T_{H_o} yields:

$$T_{AV}(t)\left[1 + 2\frac{\tau_2}{\tau_0}\right] + \tau_2 \frac{dT_{AV}(t)}{dt} = T_F(t) + 2\frac{\tau_2}{\tau_0} T_{C_i}(t) \qquad (24)$$

where $\tau_0 = \frac{C_M}{\dot{m}_M C}$, and

$\tau_2 = \frac{C_M}{h_{FM}}$

Now let

$$\begin{aligned} P(t) &= P_o + \delta P(t) \\ T_F(t) &= T_{F_o} + \delta T_F(t) \\ T_{AV}(t) &= T_{AV_o} + \delta T_{AV}(t) \\ T_{H_o}(t) &= T_{Ho_o} + \delta T_{Ho}(t) \\ T_{C_i}(t) &= T_{Ci_o} + \delta T_{C_o}(t) \end{aligned} \tag{25}$$

where the zero subscript denotes a steady state value and the prefix a small perturbation about this value.

Substituting equations (25) into equations (22), (23), and (24), eliminating the average temperatures $T_F(t)$ and $T_{AV}(t)$, and taking Laplace transforms, the following relationship between reactor coolant inlet and outlet temperature perturbations is derived (see Appendix B):

$$\delta T_{H_o}(s) = \frac{-\left\{ \frac{\tau_1 \tau_2}{2} s^2 + \left[\frac{\tau_0}{\tau_2}\left(\frac{\tau_1}{\tau_2}+1\right) - \tau_1 \right] s - 1 \right\} \delta T_{C_i}(s) + \gamma \delta P(s)}{\left\{ \frac{\tau_1 \tau_2}{2} s^2 + \left[\frac{\tau_0}{\tau_2}\left(\frac{\tau_1}{\tau_2}+1\right) + \tau_1 \right] s + 1 \right\}} \tag{26}$$

where

$$\gamma = \frac{\tau_1 \tau_0}{C_F \tau_2} = \frac{1}{\dot{m}_H C}$$

This equation is the reactor heat transfer function for the reactor coolant outlet temperature as a function of the reactor coolant inlet temperature and reactor power.

A block diagram representation of this transfer function is shown in Figure 7.

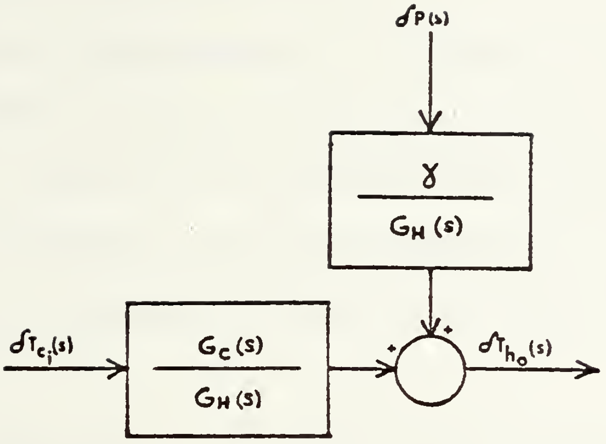


Figure 7. Block Diagram of the Reactor Heat Transfer Function

In Figure 7

$$G_C(S) = \left\{ \frac{\tau_1 \tau_2}{2} s^2 + \left[\frac{\tau_0}{\tau_2} \left(\frac{\tau_1}{\tau_2} + 1 \right) - \tau_1 \right] s + 1 \right\}$$

$$G_H(S) = \frac{1}{\left\{ \frac{\tau_1 \tau_2}{2} s^2 + \left[\frac{\tau_0}{\tau_2} \left(\frac{\tau_1}{\tau_2} + 1 \right) + \tau_1 \right] s + 1 \right\}}$$

2. Heat Exchanger Transfer Function

As in the derivation of the reactor heat transfer function, a lumped parameter model was assumed for the heat exchanger. Two points of energy storage were assumed, the primary coolant water and the water on the secondary side of the heat exchanger. The thermal capacity of the heat exchanger metal was included with that for the secondary water, since the thermal resistance on the primary side is predominant. A further assumption was made that the time spent by the primary coolant

while it passed through the heat exchanger was negligible in comparison with the time spent in the primary piping.

The state of the steam produced on the secondary side of the heat exchanger was assumed to always be dry and saturated and that the secondary water is always at the saturation temperature for the existing pressure. These assumptions were justified because moisture separators and recirculation can provide high quality steam and preheating of the feedwater.

With these assumptions, the following equations were obtained from a heat balance per unit time:

$$\dot{m}_M c \left[T_{H_i}(t) - T_{C_o}(t)\right] = C_M \frac{dT_{AV_B}(t)}{dt} + h_{TM}\left[T_{AV_B}(t) - T_S(t)\right] \qquad (27)$$

$$h_{TM}\left[T_{AV_B}(t) - T_S(t)\right] = C_S \frac{dT_S(t)}{dt} + P_L(t) \qquad (28)$$

where $T_{Hi}(t)$ = Heat exchanger coolant inlet temperature (°F)

$T_{Co}(t)$ = Heat exchanger coolant outlet temperature (°F)

$T_{AV_B}(t)$ = Heat exchanger average coolant temperature (°F)

$T_S(t)$ = Saturated steam temperature (°F)

h_{TM} = Total heat transfer coefficient (BTU/°F.sec)

C_M = Total thermal capacity of coolant in the heat exchanger (BTU/°F)

C_S = Total thermal capacity of heat exchanger metal and secondary water and steam (Btu/°F)

$P_L(t)$ = Power delivered by the heat exchanger (BTU/sec)

m_m = Coolant mass flow rate (lbm/sec)

The total heat transfer coefficient, a function of the primary coolant flow rate (a constant in the model) and the heat transfer characteristics of the heat exchanger, was assumed to be constant. Also, the time delay in transferring heat across the heat exchanger tubes was neglected. This changed the shape of the initial thermal transient but had little effect on the basic dynamics of the secondary loop.

Again, as a simplification, the average temperature of the coolant in the heat exchanger was assumed to be given by

$$T_{AV_B} = \frac{1}{2} \left(T_{H_i} + T_{C_o}\right) \qquad (29)$$

The power delivered by the steam generator is proportional to the product of the steam flow rate and the difference in enthalpy between the steam and feedwater

$$h_{TM}\left[T_{AV_B}(t) - T_S(t)\right] = \dot{m}_S \left(H_S - H_{FW}\right) + C_S \frac{dT_S(t)}{dt}$$

where $\dot{m}_S$ = Steam flow rate (lbm/sec)

H_S = Saturated steam enthalpy (Btu/lbm)

H_F = Feedwater enthalpy (Btu/lbm)

This equation assumes the steam and feedwater flow rates are always equal and thus neglects any instabilities in the secondary steam.

As discussed in Reference 4, the enthalpy of saturated steam is nearly constant over a wide range of pressure, varying from 1198 Btu/lbm to 1204 Btu/lbm over a pressure range from 200 to 800 psig. The feedwater enthalpy,which depends on condenser pressure, is usually between 50 and 100 Btu/lbm. Thus the enthalpy difference may be regarded as a

constant, and the power delivered by the heat exchanger is directly proportional to the steam flow rate.

The impedance to steam flow caused by the turbine is nearly independent of turbine speed. If constant backpressure is assumed, the steam flow rate is directly proportional to the throttle opening at a given pressure. Thus,

$$m_s = \rho_s A$$

where ρ_s = Saturated steam pressure (lbf/in^2)

A = Proportionality factor which is a function of the throttle setting $\frac{\text{lbm in}^2}{\text{lbf sec}}$

The numerous assumptions made in the heat exchanger model development limit the accuracy of the resulting equations. However, the errors involved in these assumptions are usually less than the amount of uncertainty in the engineering valves of the coefficients used in the equations.

Recalling the previous assumption that

$$\frac{dT_{AV_B}(t)}{dt} = 0 \quad , \text{ and}$$

Substituting equation (29) into equation (27), yields:

$$\dot{m}_M C\left[T_{H_i}(t) - T_{C_o}(t)\right] = h_{TM}\left\{\frac{1}{2}\left[T_{H_i}(t) + T_{C_o}(t)\right] - T_S(t)\right\} \qquad (30)$$

Solving equation (30) for T_{C_o}, gives:

$$T_{C_o}(t) = \frac{2T_S(t) - T_{H_i}(1-K_1)}{(1+K_1)} \qquad (31)$$

where $K_1 = \frac{2\dot{m}_M C}{h_{TM}}$

Substituting equation (29) into equation (28) gives:

$$h_{TM}\left\{\frac{1}{2}\left[T_{H_i}(t) + T_{C_o}(t)\right] - T_S(t)\right\} = C_S\frac{dT_S(t)}{dt} + P_L(t)$$

Rearranging this expression,

$$\frac{C_S}{h_{TM}}\frac{dT_S(t)}{dt} + T_S(t) = \frac{1}{2}\left[T_{H_i}(t) + T_{C_o}(t)\right] + \frac{1}{h_{TM}}P_L(t) \qquad (32)$$

Let

$$\begin{aligned} T_{Hi}(t) &= T_{H_{io}} + \delta T_{H_i}(t) \\ T_{C_o}(t) &= T_{C_{o_o}} + \delta T_S(t) \\ T_S(t) &= T_{X_o} + \delta T_S(t) \\ P_L(t) &= P_{L_o} + \delta P_L(t) \end{aligned} \qquad (33)$$

where the lowest zero subscript denotes a steady state value and the delta prefix a small perturbation about this value.

By substituting equations (33) into equations (31) and (32), and taking the Laplace transform, the following set of equations is derived (see Appendix C):

$$\delta T_S(s) = \frac{\frac{1}{2}\left[\delta T_{C_o}(s) + \delta T_{H_i}(s)\right] - \frac{1}{h_{TM}}\delta P_L(s)}{\tau s + 1} \qquad (34)$$

$$\delta T_{C_o}(s) = \frac{2\delta T_S(s) - \delta T_{H_i}(s)\left[1 - K_1\right]}{1 + K_1} \qquad (35)$$

where $\tau_S = \frac{C_S}{h_{TM}}$

These equations are represented in a block diagram in Figure 8.

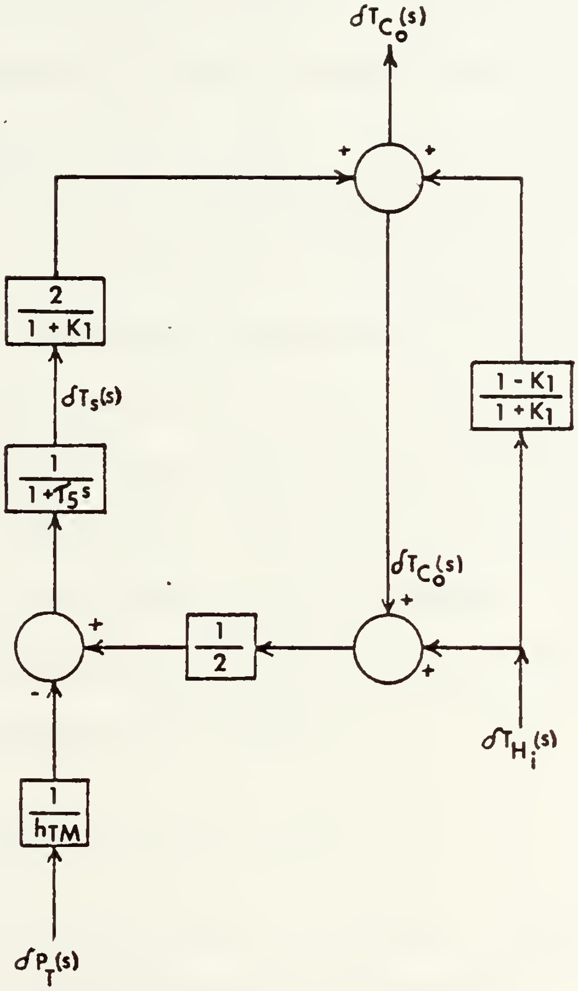


Figure 8. Block Diagram of the Heat Exchanger Transfer Function

With δT_{H_i} and δP_L as inputs, equations (34) and (35) form an algebraic loop in δT_{C_o} and δT_S. These two equations were solved with the use of an inherent functional routine available in the CSMP-III language which was used to formulate the model.

3. Primary Piping Transfer Functions

While circulating through the primary loop, the coolant undergoes mixing and transport delay effects. For example, a transient in the coolant temperature at the heat exchanger outlet does not appear at the reactor inlet until sometime later. Where there are volume or flow direction changes, as in the reactor coolant inlet plenum, mixing occurs causing a smearing of a temperature transient. Both of these effects were approximated in the model by combinations of two types of time delays: a pure transport delay and a simple mixing delay.

Assuming no mixing in the primary piping and no heat loss with perfectly insulated pipes, pure transport delays are encountered in the piping runs between the reactor and heat exchanger. With these assumptions, the temperatures involved in the transfer of heat between the reactor and heat exchanger can be given as

$$T_{H_i}(t) = T_{H_o}(t - T_3)$$

where the inlet coolant temperature to the heat exchanger T_{H_i} has the same form as the outlet temperature of the reactor T_{H_o} after a fixed transport delay τ_3. This transport delay can be approximated by the following differential equation which is derived in Appendix D.

$$T_{H_i} + \tau_3 \frac{dT_{H_i}}{dt} = T_{H_o} \qquad (36)$$

Similarly, the transport delay from the heat exchanger outlet to the reactor inlet plenum is:

$$T_{C_{ip}}(t) + \tau_4 \frac{dT_{C_{ip}}(t)}{dt} = T_{C_o}(t) \qquad (37)$$

where $T_{C_{ip}}(t)$ = Reactor inlet plenum coolant temperature (°F)

$T_{C_o}(t)$ = Heat exchanger outlet coolant temperature (°F)

This can be approximated by

$$T_{C_{ip}}(t) + \tau_4 \frac{dT_{C_{ip}}(t)}{dt} = T_{C_o}(t) \tag{37}$$

As in the previous development, let

$$\begin{aligned} T_{H_o}(t) &= T_{H_{o_o}} + \delta T_{H_o}(t) \\ T_{H_{ip}}(t) &= T_{H_{ipo}} + \delta T_{H_{ip}}(t) \\ T_{C_o}(t) &= T_{C_{o_o}} + \delta T_{C_o}(t) \\ T_{C_{ip}}(t) &= T_{C_{ipo}} + \delta T_{C_{ip}}(t) \end{aligned} \tag{38}$$

where again the lowest zero subscript denotes a steady state value and the delta prefix a small perturbation about this value.

After substituting equations (38) into equations (36) and (37), taking the Laplace transform, the following transfer functions are derived (see in Appendix D).

$$\frac{\delta T_{H_{ip}}(s)}{\delta T_{H_o}(s)} = \frac{1}{1 + \tau_3 s} \tag{39}$$

$$\frac{\delta T_{C_{ip}}(s)}{\delta T_{C_o}(s)} = \frac{1}{1 + \tau_4 s} \tag{40}$$

Combined mixing and transport effects are encountered at the reactor and heat exchanger inlet and outlet coolant plenums. For simplification, only the mixing effects at the inlet plenums were considered in the model. Assuming perfect mixing and after performing a heat balance on the plenum concerned, the combined mixing and transport effects are expressed by differential equations developed in Appendix D of the form

$$\tau \frac{dTo(t)}{dt} + T_o(t) = T_i(t)$$

where

$T_i(t)$ = Plenum inlet temperature (°F)

$T_o(t)$ = Plenum outlet temperature (°F)

τ = Mixing delay

As before, by using a small perturbation technique, and taking the Laplace transform, the following transfer function is derived (see Appendix D):

$$\frac{\delta T_{Ho}(s)}{\delta T_{H_i}(s)} = \frac{1}{1 + \tau s} \qquad (41)$$

Block diagram representations of the coolant piping transport and mixing transfer functions is shown in Figure 9.

D. OVERALL PLANT BLOCK DIAGRAM

The transfer functions developed previously for the zero power point reactor, ^{135}Xe feedback, reactor and heat exchanger heat transfer, and the primary piping were interconnected resulting in the overall model block diagram shown in Figure 10. The moderator temperature feedback

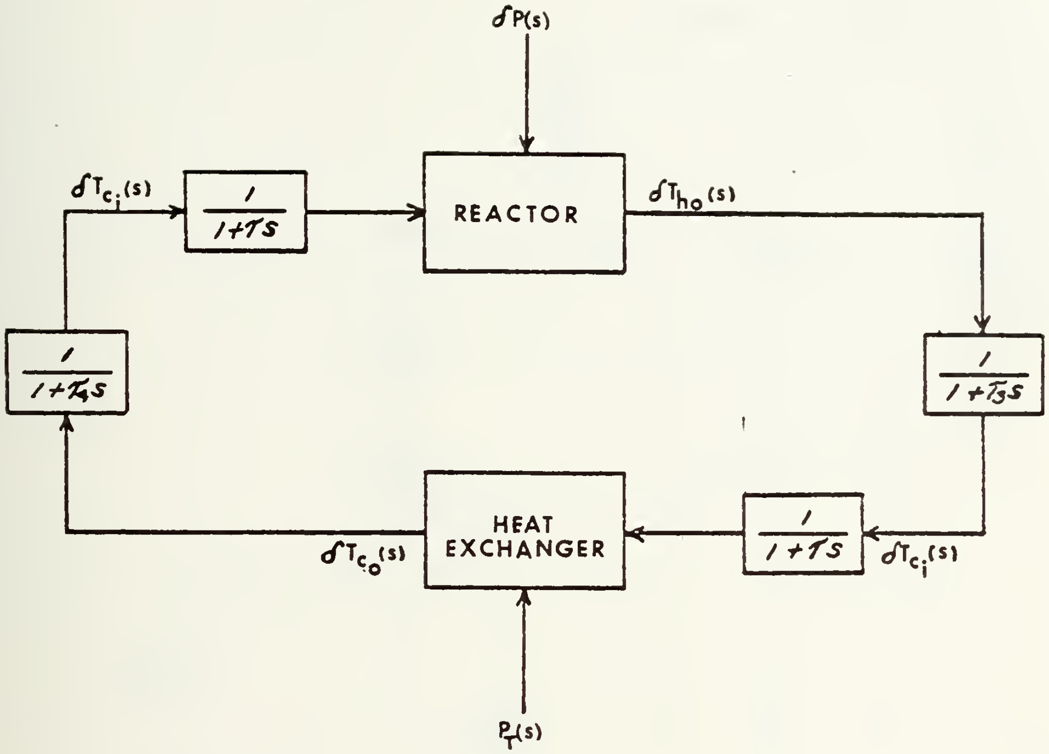


Figure 9. Block Diagram of the Transport and Mixing Delay Functions

loop is seen to consist of the heat transfer process and primary piping transfer functions which yield δT_{C_i} and δT_{H_o}. These temperatures are summed, then halved, yielding T_{AV}, which is then multiplied by the negative temperature coefficient αT, generating the moderator temperature feedback reactivity ρ_T.

E. MODEL CONSTANTS

The following plant parameters from the Shippingport Atomic Power Station were obtained from Reference 6 and used in the model development.

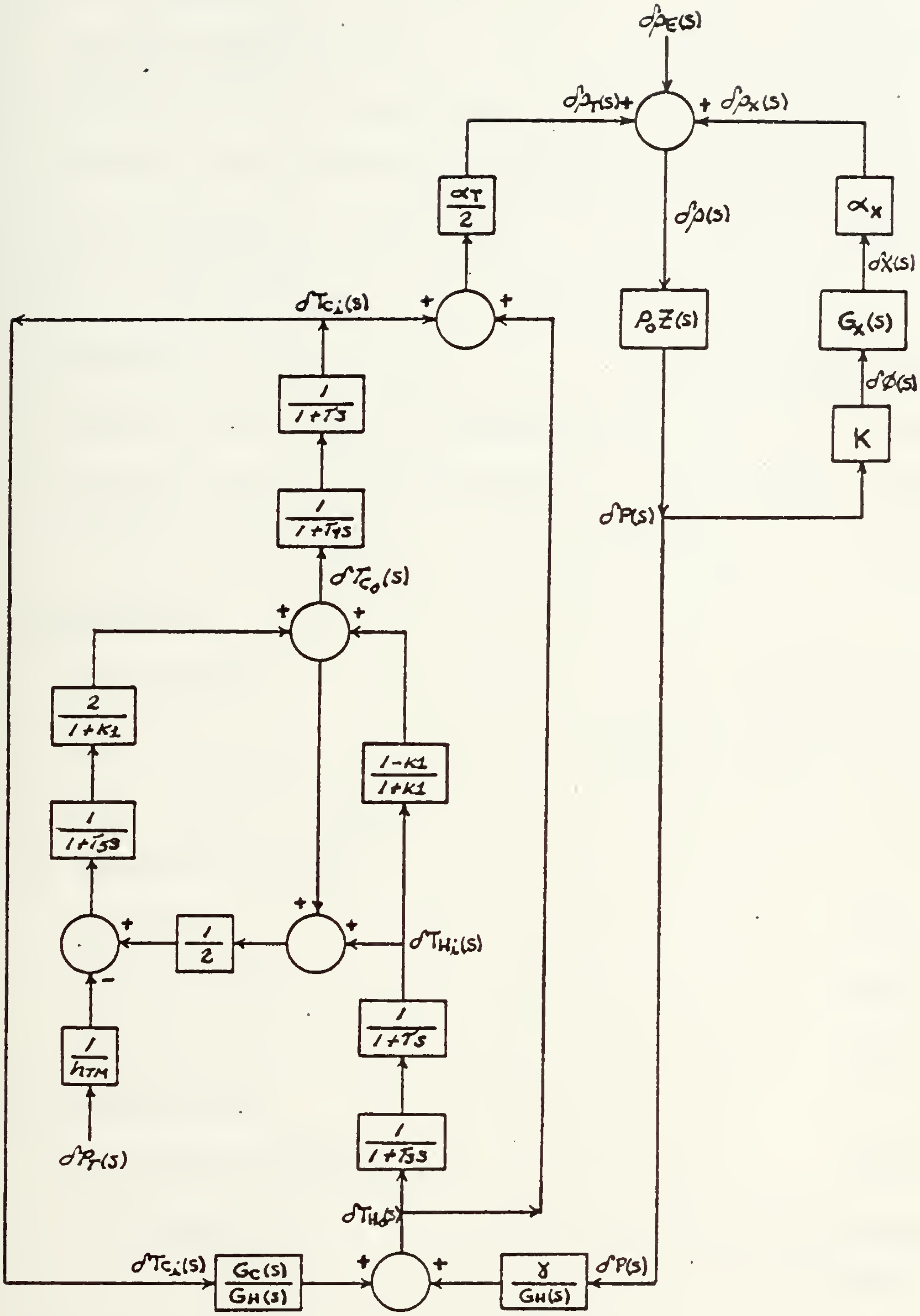


Figure 10. Overall Plant Block Diagram

1. General Parameters	
a. Reactor thermal power	231 MW
b. Reactor coolant system pressure	2000 psia
c. Reactor coolant average temperature	523° F
d. Steam pressure at full load	600 psia
2. Reactor Coolant System	
a. Reactor coolant flow rate	6280 lbm/sec
b. Reactor coolant outlet temperature	538° F
c. Reactor coolant inlet temperature	508° F
d. Coolant volume in core	103 ft^3
3. Reactor Core	
a. Configuration	Right cylinder
b. Size	6.8 ft. dia X 6 ft. high
c. Fuel load U^{235} (seed)	75 kg
d. Composition (seed)	
1) Water	43.5 v/o
2) Fuel alloy	30.0 v/o
3) Zircalloy	34.1 v/o
e. Control Rods	
1) Total rod worth	0.256 k
2) Scram time	0.35 sec time delay 1.0 sec rod drop
4. Nuclear Data	
a. Thermal neutron flux	2×10^{14} n/cm^2 sec
b. Prompt neutron lifetime	5.6×10^{-5} sec

c. Effective delayed neutron fraction	0.0077
d. Temperature coefficient of reactivity	$-3.1 \times 10^{-4}\ \delta k/°F$
5. Reactor Protection Setpoints	
a. Scram	
1) High reactor power	138%
2) High reactor coolant outlet temperature	550°F
b. Cutback	
1) High reactor power	114%
2) High Startup rate	1.74 Decades per min.

IV. RESULTS

A. INTERACTIVE PROGRAM

Figures 10-16 are examples of the interactive program output. As shown in Figure 10, the user is first given a description of the purpose of the overall program and general instructions for input entry. As shown in Figure 11, the user is then prompted to enter an initial steady state power level, after which the corresponding major plant parameters are displayed. The user is then prompted to choose the type of simulation, either plant transient at power, or post-shutdown Xenon-135 behavior. The user must be at the Tektronix 4012 console in the computer center if the latter is chosen.

If the post-shutdown Xenon-135 behavior is chosen to be examined, graphs such as those shown in Figure 13 are generated and displayed on the Tektronix's screen. In addition to showing the time response of the Xenon, the time of its peak and associated maximum reactivity are displayed.

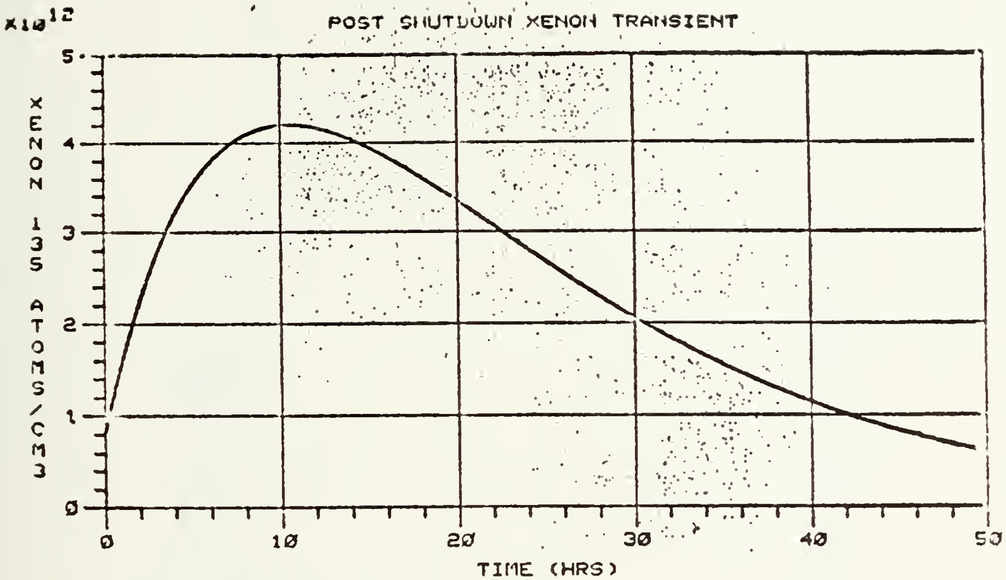
If the plant transient simulation is chosen, the user is then prompted to choose the mechanism for initiating the transient, either control rod movement or turbine load change. In Figure 14, the user has chosen the former. The program then prompts the user to enter the direction and time length of the control rod movement. In Figure 15, the turbine load change was chosen and the program request the final turbine load. In either case, a summary of the transient inputs is displayed with a notice that the interactive portion is complete.

```
EXECUTION BEGINS...

    THIS IS AN INTERACTIVE PROGRAM WHICH SIMULATES THE THERMAL RESPONSE
OF A 231 MWT (68 MWE), HIGHLY ENRICHED PRESSURIZED WATER REACTOR (PWR),
POWER PLANT TO CHANGES IN REACTIVITY INITIATED BY CHANGES IN BANK CON-
TROL ROD POSITION OR TURBINE LOAD.  THE REACTIVITY FEEDBACK EFFECTS
RESULTING FROM CHANGES IN MODERATOR TEMPERATURE AND XENON-135 CONCENTRA-
TION ARE INCORPORATED INTO THE MODEL.


PLEASE ANSWER THE FOLLOWING STATEMENTS BY ENTERING THE NUMBER (INCLUDING
THE DECIMAL POINT, BUT NOT THE PERCENT SYMBOL) WHICH CORRESPONDS TO THE
DESIRED CHOICE OR VALUE WITHIN THE GIVEN RANGE.


DO YOU WANT A BRIEF DESCRIPTION OF THE PLANT?
    1.  YES
    2.  NO
>2.
```

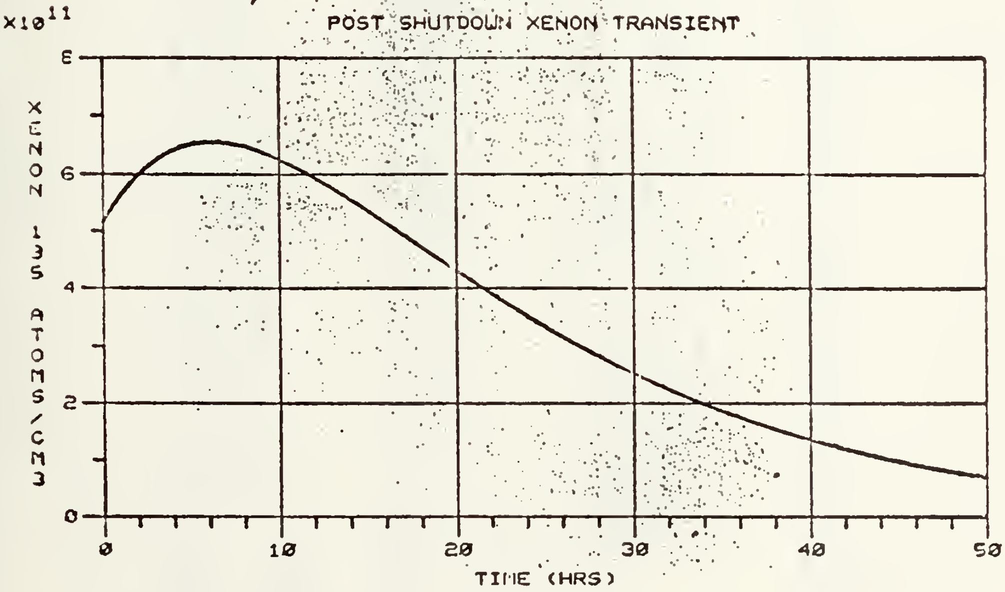
Figure 11. Interactive Program, Introduction and Instructions

```
ENTER AN INITIAL STEADY STATE POWER LEVEL BETWEEN 10. AND 100. PERCENT.
NOTE: A MINIMUM OF 10% POWER IS REQUIRED TO OPERATE THE REACTOR COOLANT
      PUMPS AND OTHER PLANT AUXILIARIES
>50.

INITIAL STEADY STATE PARAMETERS:
    REACTOR POWER= 50.00% 115.50 MWE
    THERMAL NEUTRON FLUX= 0.10E 15 NEUTRONS/CM2 SEC
    XENON-135 CONCENTRATION= 0.76E 12 ATOMS/CM3
    FUEL TEMPERATURE=711.50 F
    AVERAGE REACTOR COOLANT MODERATOR) TEMPERATURE=523.00 F
    REACTOR COOLANT OUTLET TEMPERATURE=530.50 F
    REACTOR COOLANT INLET TEMPERATURE=515.50 F
    SATURATED STEAM TEMPERATURE=504.54 F
    SATURATED STEAM PRESSURE=704.07 PSIA
    TURBINE LOAD= 50.00% 34.00 MWE


ENTER THE DESIRED SIMULATION:
    1.  MODERATOR TEMPERATURE AND XENON FEEDBACK AT POWER
    2.  POST SHUTDOWN XENON BEHAVIOR
>1.
```

Figure 12. Interactive Program, Initial Power Level and Simulation Choice Inputs



```
PRE-SHUTDOWN POWER = 100.00%
PEAK XENON TIME =  10.43 HRS
PEAK XENON LEVEL = 0.953E 12 ATOMS/CM3
PEAK XENON REACTIVITY = 0.500E-01 DELTA K
```



```
PRE-SHUTDOWN POWER =  10.00%
PEAK XENON TIME =    6.15 HRS
PEAK XENON LEVEL = 0.520E 12 ATOMS/CM3
PEAK XENON REACTIVITY = 0.272E-01 DELTA K
```

Figure 13. Post-shutdown Xenon-135 Behavior

```
ENTER THE INITIAL REACTIVITY CHANGE MECHANISM:
    1.  BANK CONTROL ROD CHANGE
    2.  TURBINE LOAD CHANGE
>1.



ENTER THE TIME LENGTH (SEC) OF BANK CONTROL ROD MOVEMENT (TSHIM)
NOTE: BANK CONTROL ROD REACTIVITY INSERTION RATE IS 1.25E-4 DELTA K/SEC,
      DO NOT EXCEED A TOTAL REACTIVITY INSERTION OF 35.0E-4 DELTA K
      (I.E. A 28 SEC SHIM)
>10.



ENTER THE DIRECTION OF BANK CONTROL ROD SHIM:
    1.  IN (NEGATIVE REACTIVITY INSERTION)
    2.  OUT (POSITIVE REACTIVITY INSERTION)
>2.



INITIAL REACTIVITY CHANGE PARAMETERS:
    REACTOR POWER =  50.00 %
    SHIM TIME =  10.00 SEC
    SHIM DIRECTION =   1.00 (1='OUT', -1='IN')
    FINAL TURBINE LOAD =  50.00%



INPUTS HAVE BEEN ENTERED INTO THE SIMULATION PROGRAM WHICH HAS BEEN SENT
TO THE BATCH SYSTEM FOR EXECUTION
R;
>
```

Figure 14. Interactive Program, Control Rod Movement Inputs

```
ENTER THE INITIAL REACTIVITY CHANGE MECHANISM:
    1.  BANK CONTROL ROD CHANGE
    2.  TURBINE LOAD CHANGE
>2.


ENTER FINAL TURBINE LOAD BETWEEN 10. AND 100. PERCENT
NOTE: LOAD VARIATION WILL OCCUR AT A FIXED RATE OF 0.5%/SEC
>75.


INITIAL REACTIVITY CHANGE PARAMETERS:
    REACTOR POWER =  50.00 %
    SHIM TIME =    0.0  SEC
    SHIM DIRECTION =  -0.25 (1='OUT', -1='IN')
    FINAL TURBINE LOAD =  75.00%


INPUTS HAVE BEEN ENTERED INTO THE SIMULATION PROGRAM WHICH HAS BEEN SENT
TO THE BATCH SYSTEM FOR EXECUTION
R;
>
```

Figure 15. Interactive Program, Turbine Load Change Inputs

Figure 16 is an example of the interactive program's logic routines which will only permit inputs within the requested ranges to be accepted for the simulation.

B. SIMULATION PROGRAM

The program generates Versatec plots showing the plant's power, reactivity, and temperature transient responses for the user's inputs. Figures 17-20 are composites of these plots.

In Figure 17, the transient was initiated by a simulated 20 to 40 percent ramp change in turbine load at 1/2 percent per second. In Figure 18, the transient was initiated by a simulated 60 to 40 percent change in turbine load in the same manner. Both of these figures show the characteristic power demand following and inherent stability response typical of a PWR plant with a constant average temperature program and negative temperature coefficient.

The inherent stability feature is further displayed in Figures 19 and 20. In Figure 19, the transient is initiated by a simulated 10 second inward movement of the control rods at a reactivity insertion rate of 1.25×10^{-4} δk per second from an initial 50 percent power level. In Figure 20, the transient response to an outward control rod movement with the same parameters is shown. As seen in both cases, the reactor power stabilizes about the initial turbine load and the average reactor coolant temperature stabilizes at a new level to compensate, via the negative temperature coefficient, for the reactivity inserted by the control rods.

```
ENTER AN INITIAL STEADY STATE POWER LEVEL BETWEEN 10. AND 100. PERCENT.
NOTE: A MINIMUM OF 10% POWER IS REQUIRED TO OPERATE THE REACTOR COOLANT
      PUMPS AND OTHER PLANT AUXILIARIES
>150.

INCORRECT DATA ENTERED


ENTER AN INITIAL STEADY STATE POWER LEVEL BETWEEN 10. AND 100. PERCENT.
NOTE: A MINIMUM OF 10% POWER IS REQUIRED TO OPERATE THE REACTOR COOLANT
      PUMPS AND OTHER PLANT AUXILIARIES
>5.

INCORRECT DATA ENTERED


ENTER AN INITIAL STEADY STATE POWER LEVEL BETWEEN 10. AND 100. PERCENT.
NOTE: A MINIMUM OF 10% POWER IS REQUIRED TO OPERATE THE REACTOR COOLANT
      PUMPS AND OTHER PLANT AUXILIARIES
>50.
```

Figure 16. Interactive Program, Logic Routine Example

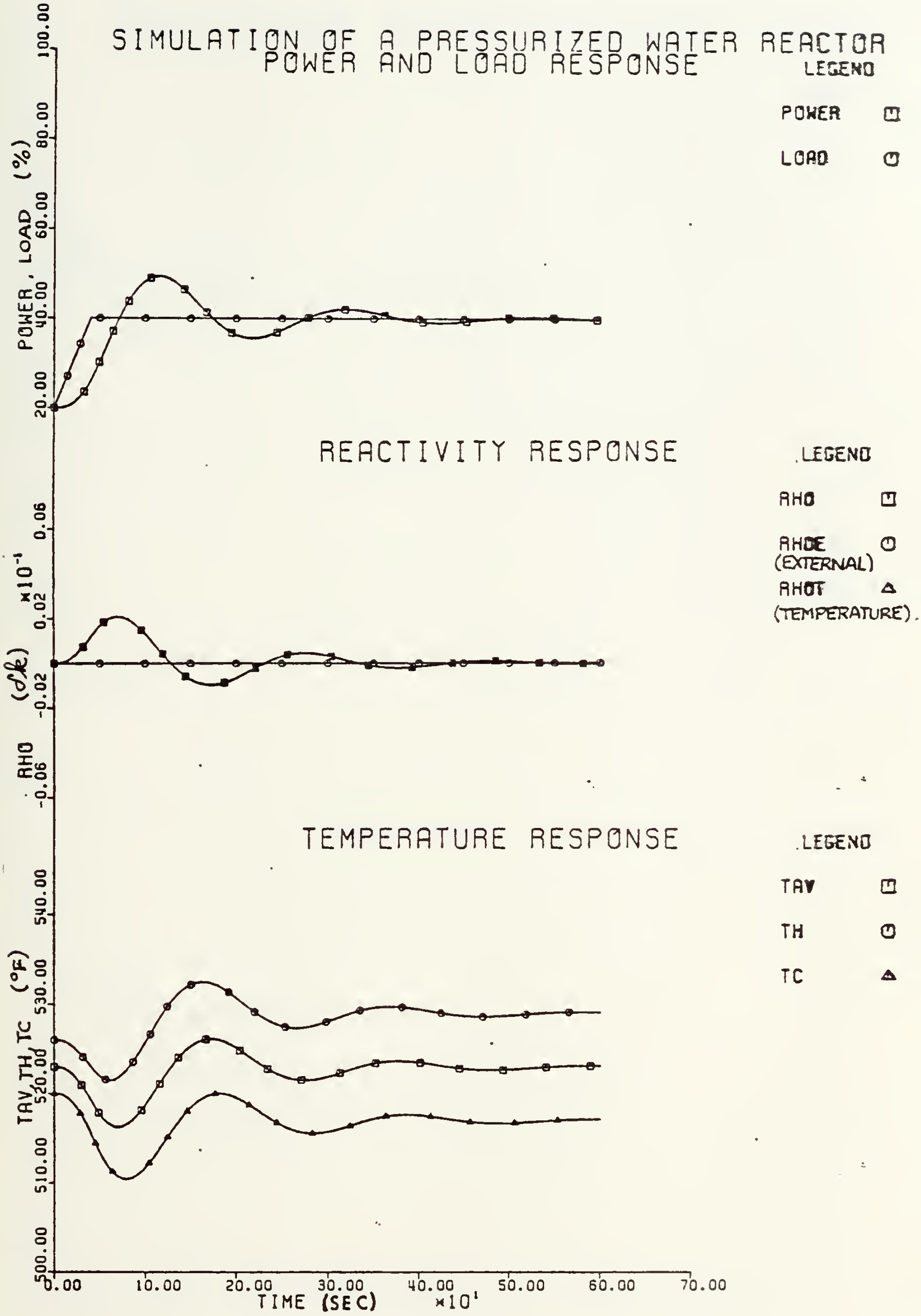


Figure 17. Power, Reactivity, and Temperature Response to a 20 to 40% Turbine Load Change

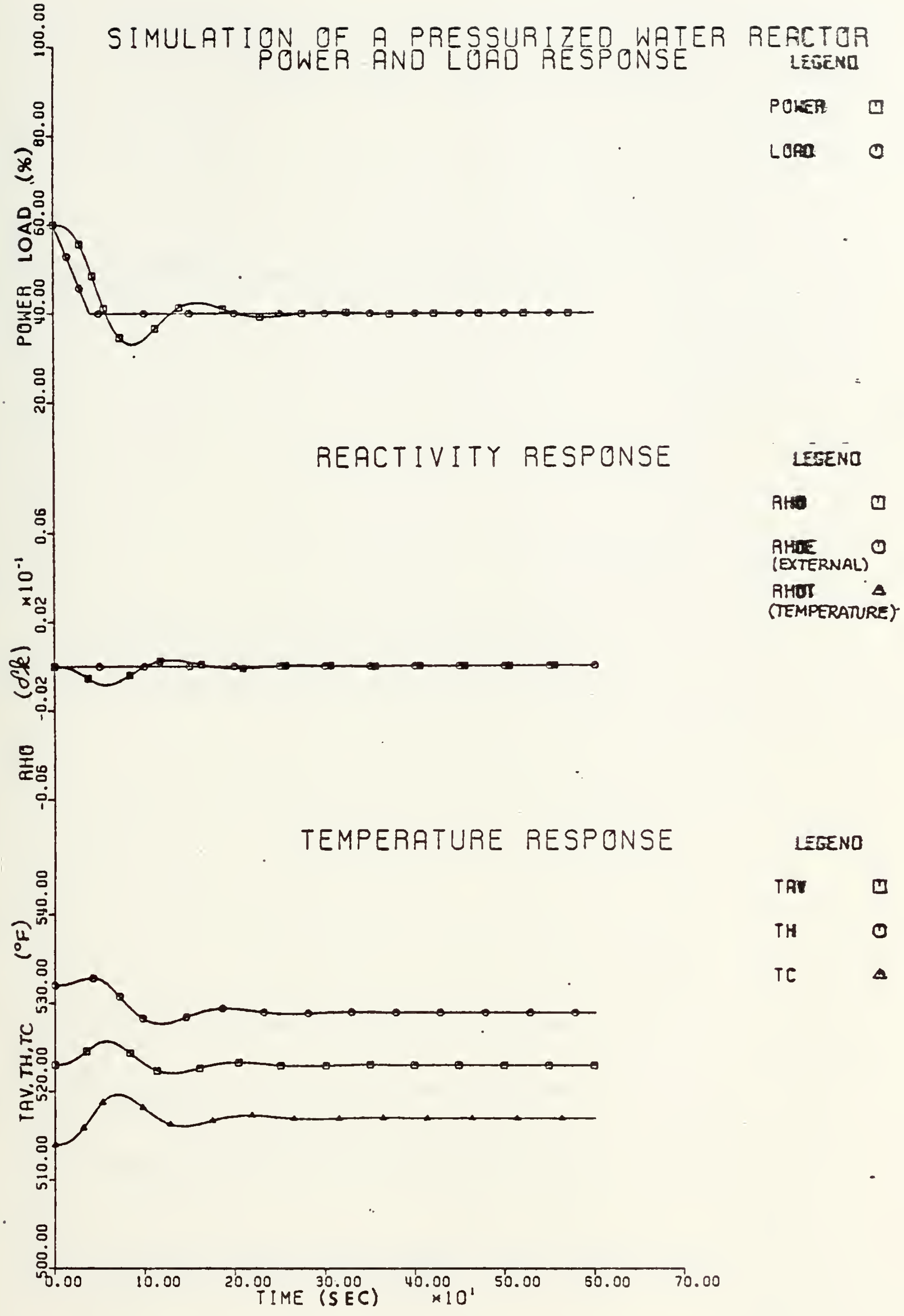


Figure 18. Power, Reactivity, and Temperature Response to a 60 to 40% Turbine Load Change

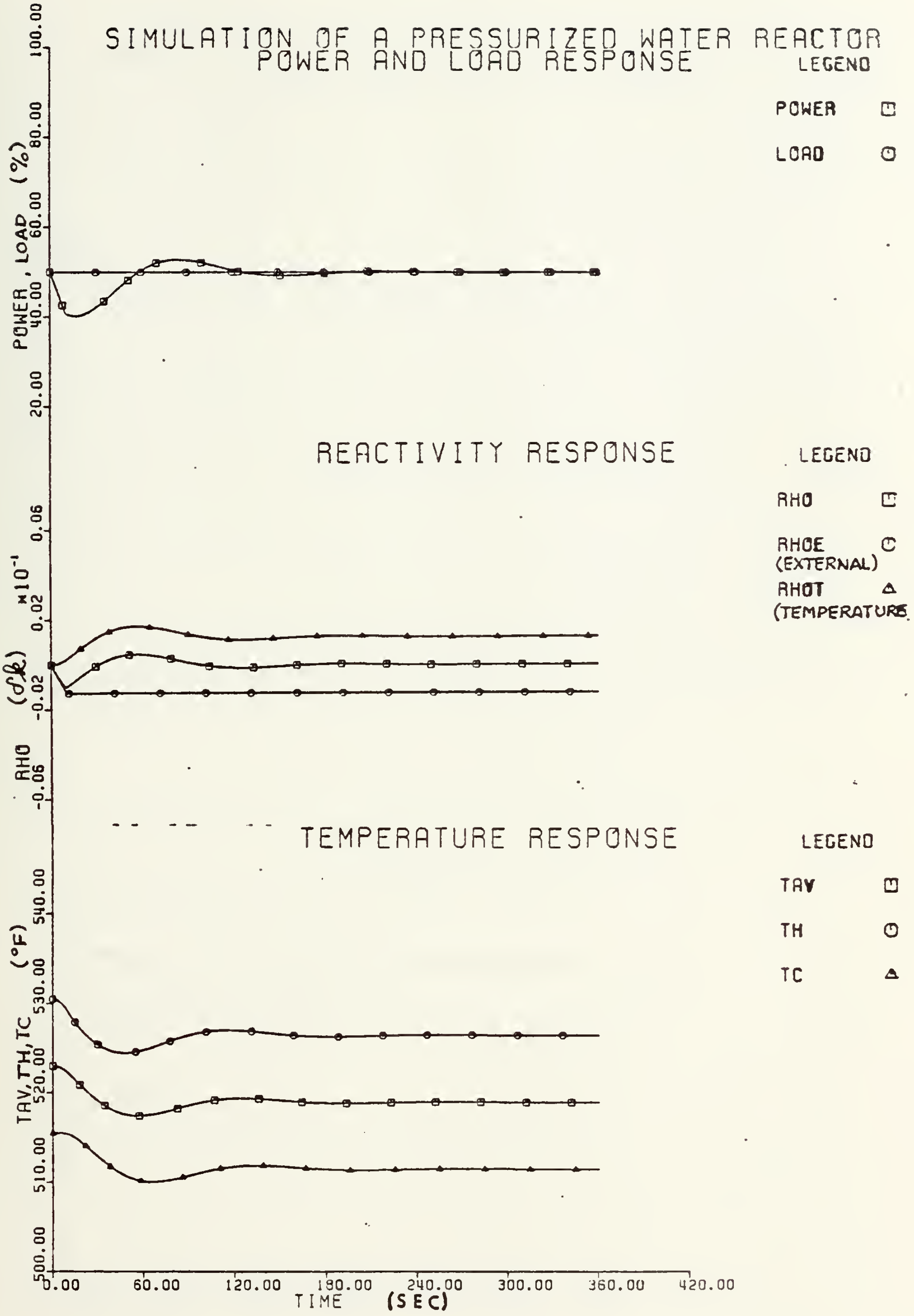


Figure 19. Power, Reactivity, and Temperature Response to a 10 second Inward Control Rod Movement

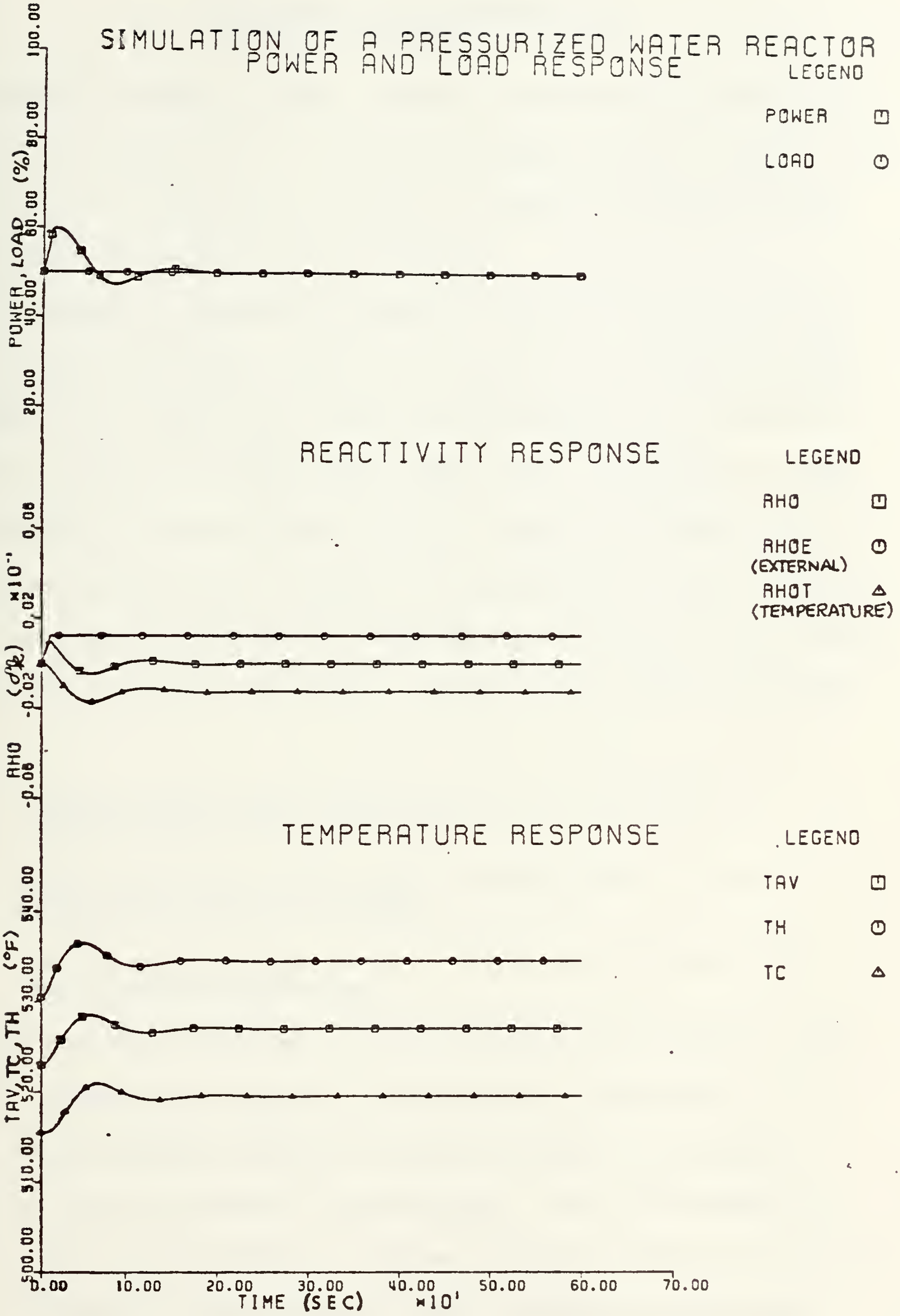


Figure 20. Power, Reactivity, and Temperature Response to a 10 second Outward Control Rod Movement

V. CONCLUSIONS AND RECOMMENDATIONS

The model responds to normal operating transients with the characteristics of a PWR plant. The interactive program provides the user with the facility to initiate the simulation or examine a real time display of post-shutdown Xenon-135 buildup and decay.

As previously discussed, the purpose of this work was to develop a learning device for nuclear engineering students at the Naval Postgraduate School. The result was a relatively simple model of a PWR power plant and a simulation program that suffers from a long execution time.

The model's simplicity resulted mainly from the consideration of an effective single group of delayed neutron precursors in the reactor kinetic equations and the use of lumped parameter analysis in the plant's heat transfer processes. The model's sophistication could be increased by:

1. Expanding the reactor kinetic equations to consider six delayed neutron precursor groups.
2. Developing a multi-section heat transfer model for the reactor and the heat exchanger.
3. Incorporating variable reactor coolant mass flow rate and heat transfer coefficients.

These additional features will also increase the complexity of the simulation program, thus aggravating the long run time problem. This concern might be eased by taking a different approach to the model's formulation than the transfer function method. While this method was readily coded using the CSMP-III language, physical insight to the plant dynamic processes was lost when the Laplace transform and subsequent grouping of constant terms was performed. The use of state variable

theory might not only allow this physical appreciation to be retained but also result in shorter program run times.

Regardless of the formulation method, a real time response to the simulation can probably only be achieved by using an analog computer. The wide range of time constants associated with the equations (prompt neutron life-times on the order of 10^{-5} seconds to Xenon decay half lives on the order of hours) require a small numerical integration time interval over a large time period. The result is a prohibitively long run time on a digital computer for an interactive program.

It is hoped that refinement of the model will be continued. While the existing model does reflect the general characteristics of a PWR plant to normal operating transients, it does exhibit relatively large power over/under shoots in response to turbine load changes as seen in Figures 17 and 18.

APPENDIX A

DEVELOPMENT OF THE XENON FEEDBACK TRANSFER FUNCTION COMPONENTS

1. Derivation of $G_X(S)$

The previously developed rate equations for ^{135}I and ^{135}Xe from the effective ^{135}Xe decay scheme shown in Figure 5 are:

$$\frac{dI}{dt} = \gamma_I \Sigma_f \phi(t) - \lambda_I I(t) \qquad \text{(A 1)}$$

$$\frac{dX}{dt} = \gamma_X \Sigma_f \phi(t) + \lambda_I I(t) - \lambda_X X(t) - \sigma_a^X \phi(t) X(t) \qquad \text{(A 2)}$$

where $I(t)$ = ^{135}I number density (atoms/cm^3)

$X(t)$ = ^{135}Xe number density (atoms/cm^3)

Σf = Macroscopic fission cross section of ^{235}U (cm^{-1})

ϕ = Average integrated one group flux (neutrons/cm^{2}sec)

γ_I = Effective ^{135}I fission yield

γ_X = Effective ^{135}Xe fission yield

λ_I = ^{135}I decay constant (sec^{-1})

λ_X = ^{135}Xe decay constant (sec^{-1})

σ_a^X = ^{135}Xe thermal neutron absorption cross section (cm^2)

Let

$$I(t) = I_0 + \delta I(t)$$
$$X(t) = X_0 + \delta X(t) \qquad \text{(A 3)}$$
$$\phi(t) = \phi_0 + \delta\phi(t)$$

where the zero subscript denotes an initial steady state value and the delta prefix denotes a small perturbation about this value.

With the reactor at an initial steady state with a flux level ϕ_0, the equilibrium values of ^{135}I and ^{135}Xe are found by setting their time dependence in equations (A 1) and (A 2) equal to zero. Thus,

$$I_0 = \frac{\gamma_I \Sigma_f \phi_0}{\lambda_I} \tag{A 4}$$

$$X_0 = \frac{\gamma_X \Sigma_f \phi_0 + \lambda_I I_0}{\lambda_X + \sigma_a^X \phi_0} \tag{A 5}$$

Substituting equation (A 4) into equation (A 5)

$$X_0 = \frac{(\gamma_X + \gamma_I) \Sigma_f \phi_0}{\lambda_X + \sigma_a^X \phi_0} \tag{A 6}$$

Substituting equations (A 3), (A 4), and (A 6) into equation (A 1) and (A 2), neglecting the $\delta\phi \; \delta X$ term (first order approximation)

$$\frac{d}{dt} \delta I = \gamma_I \Sigma_f \delta\phi - \lambda_I \delta I \tag{A 7}$$

$$\frac{d}{dt} \delta X = \lambda_I \delta I + (\gamma_X \Sigma_f - \sigma_a^X X_0) \delta\phi - (\lambda_X + \sigma_a^X \phi_0) \delta X \tag{A 8}$$

Taking the Laplace transform of equations (A 7) and (A 8) and solving for $\delta I(S)$ and $\delta X(S)$

$$\delta I(s) = \frac{\gamma_I \Sigma_f \delta\phi(s)}{s + \lambda_I} \tag{A 9}$$

$$\delta X(s) = \frac{\lambda_I \delta I(s) + (\gamma_X \Sigma_f - \sigma_a^X X_0) \delta\phi(s)}{(s + \lambda_X + \sigma_a^X \phi_0)} \tag{A10}$$

Substituting equation (A 9) into equation (A10)

$$\delta X(s) = \frac{\lambda_I \gamma_I \Sigma_f \delta\phi(s) + (s+\lambda_I)(\gamma_X \Sigma_f - \sigma_a^X X_0)\delta\phi(s)}{(s+\lambda_I)(s+\lambda_X+\sigma_a^X \phi_0)}$$

Expanding, collecting terms, and solving for $\frac{\delta X(s)}{\delta\phi(s)}$

$$\frac{\delta X(s)}{\delta\phi(s)} = \frac{(\gamma_X \Sigma_f - \sigma_a^X X_0)s + \lambda_I(\gamma_I \Sigma_f + \gamma_X \Sigma_f - \sigma_a^X X_0)}{s^2 + (\sigma_a^X \phi_0 + \lambda_X + \lambda_I)s + \lambda_I(\sigma_a^X \phi_0 + \lambda_X)} = G_X(s)$$

This is equation (16) on page 23.

2. Derivation of α_x

The effective core neutron multiplication factor k is given by the familiar "six factor formula" found in the literature

$$k = \eta \epsilon p f P_{FNL} P_{TNL} \qquad \text{(A 11)}$$

where η = Thermal fission factor of the fule

ϵ = Fast fission factor of the fuel

p = Resonance escape probability

f = Thermal utilization factor in the core

P_{FNL} = Fast neutron non-leakage probability

P_{TNL} = Thermal neutron non-leakage probability

The core reactivity is defined as

$$\rho = \frac{k-1}{k} \qquad \text{(A 12)}$$

Consider a reactor at an initial critical steady state condition with an equilibrium ^{135}Xe concentration Xo. By the definition of criticality

$$ko = 1 \qquad (A\ 13)$$
$$\rho o = 0$$

In this condition

$$f_o = \frac{\Sigma_a^F}{\Sigma_{a_o}^{core}} \approx \frac{\Sigma_a^F}{\Sigma_a^F + \Sigma_a^{X_o}} \qquad (A\ 14)$$

where Σ_a^F = Fuel macroscopic thermal neutron absorption cross section

$\Sigma_{a_o}^{core}$ = Initial core macroscopic thermal neutron absorption cross section

Σ_a^{Xo} = Initial ^{135}Xe macroscopic thermal neutron absorption cross section

and the macroscopic thermal neutron absorption cross sections of the moderator and other core materials has been neglected, a reasonable approximation in a highly enriched core.

Now impose a small perturbation in the ^{135}Xe concentration on the core. Neglecting the effect of the ^{135}Xe perturbation on neutron leakage, a reasonable assumption for a large reactor,

$$X = Xo + \delta X$$

$$k = ko + \delta k$$

$$f = fo + \delta f$$

$$\rho = \rho_o + \delta\rho = \delta\rho \quad \text{since } \rho_o = 0$$

The remainder of the terms in equation (A 11) are unchanged, thus

$$\delta k = \delta f$$

and

$$\frac{k}{ko} = \frac{f}{fo} = k \quad \text{since } ko = 1$$

where

$$f = \frac{\Sigma_a^F}{\Sigma_a^{core}} = \frac{\Sigma_a^F}{\Sigma_{a_0}^{core} + \sigma_a^X \delta X} \qquad \text{(A 15)}$$

from equation (A 12) and (A 13)

$$\delta\rho = \delta\rho_X = \frac{k-1}{k} = 1 - \frac{1}{k} \qquad \text{(A 16)}$$

substituting equations (A 14) and (A 15) into equation (A 16)

$$\delta\rho_X = 1 - \frac{\Sigma_{a_0}^{core} + \sigma_a^X \delta X}{\Sigma_{a_0}^{core}} = - \frac{\sigma_a^X \delta X}{\Sigma_{a_0}^{core}} = - \frac{\sigma_a^X \delta X}{\sigma_a^X X_0 + \Sigma_a^F}$$

or

$$\frac{\delta\rho_X}{\delta X} = - \frac{1}{X_0 + \frac{\sigma_a^u}{\sigma_a^X} U} = \alpha_X$$

This is equation (17) on page 23. Since fuel depletion effects are not considered during the short simulated transients, the fuel number density U is assumed constant and α_X is invariant in the time and the Laplace domains.

APPENDIX B

DEVELOPMENT OF THE REACTOR HEAT TRANSFER FUNCTIONS

The previously developed equations describing heat transfer from the reactor to the coolant are

$$T_F(t) + \tau_1 \frac{dT_F(t)}{dt} = T_{AV}(t) + \frac{\tau_1}{C_F} P(t) \qquad \text{(B 1)}$$

$$T_{AV}(t)\left[1 + 2\frac{\tau_2}{\tau_0}\right] + \tau_2 \frac{dT_{AV}(t)}{dt} = T_F(t) + 2\frac{\tau_2}{\tau_0} T_{C_i}(t) \qquad \text{(B 2)}$$

$$T_{AV}(t) = \frac{1}{2}\left[T_{H_o}(t) + T_{C_i}(t)\right] \qquad \text{(B 3)}$$

where $T_F(t)$ = Average core material temperature (°F)

$T_{AV}(t)$ = Average reactor coolant temperature (°F)

$T_{Ho}(t)$ = Reactor coolant outlet temperature (°F)

$T_{ci}(t)$ = Reactor coolant inlet temperature (°F)

$P(t)$ = Total power generated in the core (Btu/sec)

C_F = Total thermal capacity of core materials (Btu/°F)

C_M = Total thermal capacity of coolant in the core (Btu/°F)

C = Specific heat of coolant (Btu/blm°F)

$\dot{m}_m$ = Coolant mass flow rate (lbm/sec)

h_{FM} = Total heat transfer coefficient (Btu/sec°F)

and

$$\tau_0 = \frac{C_M}{\dot{m}_M C}$$

$$\tau_1 = \frac{C_F}{h_{FM}}$$

$$\tau_2 = \frac{C_M}{h_{FM}}$$

Let

$$\begin{aligned} P(t) &= P_o + \delta P(t) \\ T_F(t) &= T_{fo} + \delta T_F(t) \\ T_{AV}(f) &= T_{AV} + \delta T_{AV}(t) \\ T_{Ho}(t) &= T_{Ho_o} + \delta T_{Ho}(t) \\ Tc_i(t) &= Tc_{io} + \delta Tc_i(t) \end{aligned} \qquad \text{(B 4)}$$

where the lowest zero subscript denotes a steady state value and the delta prefix a small perturbation about this value.

From substitution of equations (B 4) into equations (B 1), (B 2), and (B 3), with the reactor in a steady state at $t \leq 0$,

$$\begin{aligned} T_{F_o} &= T_{AV_o} + \frac{\tau_1}{C_F} P_o \\ T_{AV_o}\left(1 + 2\frac{\tau_2}{T_o}\right) &= T_{F_o} + 2\frac{\tau_2}{T_o} Tc_{i_o} \\ T_{AV_o} &= \frac{1}{2}\left(T_{Ho_o} + Tc_{i_o}\right) \end{aligned} \qquad \text{(B 5)}$$

and

$$\begin{aligned} &\delta P(0) = 0 \\ &\delta T_F(0) = \delta T_{AV}(0) = \delta T_{Ho}(0) = \delta Tc_i(0) = 0 \end{aligned} \qquad \text{(B 6)}$$

Impose the perturbations at t=0. Substituting equations (B 4) and (B 5) into equations (B 1), (B 2), and (B 3) with the initial conditions given in equations (B 6),

$$\delta T_F(t) + \tau_1 \frac{d}{dt}\delta T_F(t) = \delta T_{AV}(t) + \frac{\tau_1}{C_F}\delta P(t) \qquad \text{(B 7)}$$

$$\delta T_{AV}(t)\left[1 + 2\frac{\tau_2}{T_o}\right] + \tau_2 \frac{d}{dt}\left[\delta T_{AV}(t)\right] = \delta T_F(t) + 2\frac{\tau_2}{T_o}\delta Tc_i(t) \qquad \text{(B 8)}$$

$$\delta T_{AV}(t) = \frac{1}{2}\left[\delta T_{Ho}(t) + \delta Tc_i(t)\right] \qquad \text{(B 9)}$$

Taking the Laplace transform of equations (B 7), (B 8), and (B 9) with the initial conditions given by equations (B 6)

$$T_F(s)\left[s\tau_1+1\right] = T_{AV}(s) + \frac{\tau_1}{C_F}P(s) \qquad \text{(B 10)}$$

$$T_{AV}(s)\left[s\tau_2+1+2\frac{\tau_2}{T_0}\right] = T_F(s) + 2\frac{\tau_2}{T_0}T_C(s) \qquad \text{(B 11)}$$

$$T_{AV}(s) = \frac{1}{2}\left[T_H(s)+T_C(s)\right] \qquad \text{(B 12)}$$

where the delta prefix and lowest subscript have been deleted for readability

Substituting equation (B 12) into equations (B 10) and (B 11)

$$T_F(s\tau_1+1) = \frac{1}{2}(T_H+T_C) + \frac{\tau_1}{C_F}P \qquad \text{(B 13)}$$

$$\frac{1}{2}(T_H+T_C)\left(s\tau_2+1+2\frac{\tau_2}{T_0}\right) = T_F + 2\frac{\tau_2}{T_0}T_C \qquad \text{(B 14)}$$

where the s domain dependence notation has been deleted for readability.

Solving equation (B 13) for T_F and substituting into equation (B 14)

$$\frac{1}{2}(T_H+T_C)\left(s\tau_2+1+2\frac{\tau_2}{T_0}\right)(s\tau_1+1) = \frac{1}{2}(T_H+T_C) + \frac{\tau_1}{C_F}P + 2\frac{\tau_2}{T_0}(s\tau_1+1)T_C$$

After expanding the products and collecting terms

$$T_H\left[s^2\frac{\tau_1\tau_2}{2}+\left(\frac{\tau_2}{2}+\frac{\tau_1}{2}+\frac{\tau_1\tau_2}{T_0}\right)s+\frac{\tau_2}{T_0}\right] = -T_C\left[s^2\frac{\tau_1\tau_2}{2}+\left(\frac{\tau_2}{2}+\frac{\tau_1}{2}-\frac{\tau_1\tau_2}{T_0}\right)s-\frac{\tau_2}{T_0}\right]+\frac{\tau_1}{C_F}P$$

After multiplying through by   and solving for $T_H(\delta T_{H_0}(s))$

$$\delta T_{H_0}(s) = \frac{-\left\{\frac{\tau_1\tau_2}{2}s^2+\left[\frac{\tau_0}{\tau_2}\left(\frac{\tau_1}{\tau_2}+1\right)-\tau_1\right]s-1\right\}\delta T_{C_i}(s)+\gamma\,\delta P(s)}{\left\{\frac{\tau_1\tau_2}{2}s^2+\left[\frac{\tau_0}{\tau_2}\left(\frac{\tau_1}{\tau_2}+1\right)+\tau_1\right]s+1\right\}}$$

where $\gamma = \frac{T_1 T_0}{c_p T_2}$ and all notation has been restored.

This is equation (26) on page 28.

APPENDIX C

DEVELOPMENT OF THE HEAT EXCHANGER TRANSFER FUNCTION

The previously derived heat exchanger heat transfer equations are

$$T_{C_o}(t) = \frac{2T_S(t) - T_{H_i}(t)\left[1 - K_1\right]}{\left[1 + K_1\right]} \qquad \text{(C 1)}$$

$$\frac{C_S}{h_{TM}} \frac{dT_S(t)}{dt} + T_S(t) = \frac{1}{2}\left[T_{H_i}(t) + T_{C_o}(t)\right] + \frac{1}{h_{TM}} P_L(t) \qquad \text{(C 2)}$$

where $T_{Hi}(t)$ = Heat exchanger coolant inlet (°F)

$T_{Co}(t)$ = Heat exchanger coolant outlet (°F)

$T_S(t)$ = Saturated steam pressure (PSIQ)

$P_L(t)$ = Power delivered by heat exchanger (Btu/sec)

C_S = Total thermal capacity of heat exchanger metal and secondary water and steam (Btu/°F)

C = Specific heat of coolant (Btu/lbm°F)

h_{TM} = Total heat transfer coefficient (Btu/°F.sec)

$\dot{m}_m$ = Coolant mass flow rate (lbm/sec)

and

$$K_1 = \frac{2\dot{m}_M C}{h_{TM}}$$

Let

$$\begin{aligned} T_{Hi}(t) &= T_{Hi_o} + \delta T_{Hi}(t) \\ T_{Co}(t) &= T_C + \delta T_{Ho}(t) \\ T_S(t) &= T_S + \delta T_S(t) \\ P_L(t) &= P_{L_o} + \delta P_L(t) \end{aligned} \qquad \text{(C 3)}$$

where the lowest zero subscript denotes a steady state value and the delta prefix a small perturbation about this value.

With the plant in an initial steady state at t ≤ 0, equations (C 1) and (C 2) are

$$T_{Co_o} = \frac{2T_{S_o} - T_{Hi_o}\left[1 + K_1\right]}{\left[1 + K_1\right]} \tag{C 4}$$

$$T_{S_o} = \frac{1}{2}\left(T_{Hi_o} + T_{Co_o}\right) + \frac{1}{h_{TM}} P_{L_o} \tag{C 5}$$

and

$$\begin{gathered} \delta P_{L_o}(0) = 0 \\ \delta T_{Hi}(0) = \delta T_{Co}(0) = \delta T_S(0) = 0 \end{gathered} \tag{C 6}$$

Impose the perturbations substituting equations (C 3), (C 4), and (C 5) into equations (C 1) and (C 2)

$$\delta T_{Co} = \frac{2\delta T_S - \delta T_{Hi}\left(1 - K_1\right)}{\left(1 + K_1\right)} \tag{C 7}$$

$$\frac{C_S}{h_{TM}} \frac{d}{dt} \delta T_S(t) + \delta T_S(t) = \frac{1}{2}\left[\delta T_{Hi}(t) + \delta T_{Co}(t)\right] - \frac{1}{h_{TM}} \delta P_L(t) \tag{C 8}$$

Taking the Laplace transforms of equations (C 7) and (C 8) with the initial conditions given by equation (C 6)

$$\delta T_S(s) = \frac{\frac{1}{2}\left[\delta T_{Co}(s) + \delta T_{Hi}(s)\right] - \frac{1}{h_{TM}} \delta P_L(s)}{\tau_S s + 1}$$

where $\tau_S = \frac{C_S}{h_{TM}}$

$$\delta T_{Co}(s) = \left\{2\delta T_S(s) - \delta T_{Hi}(s)\left[1 - K_1\right]\right\} / \left[1 + K_1\right]$$

These are equations (34) and (35) on page 33.

APPENDIX D

DEVELOPMENT OF THE PRIMARY PIPING TRANSFER FUNCTIONS

1. Transport Delay Transfer Functions

The transport delay of the coolant between the outlet of the reactor and the heat exchanger inlet plenum can be expressed as

$$T_{Hi_p}(t) = T_{Ho}(t-\tau_3) \qquad \text{(D 1)}$$

where $T_{Hi_p}(t)$ = Heat exchanger inlet plenum coolant temperature (°F)

$T_{Ho}(t)$ = Reactor coolant outlet temperature (°F)

$\tau 3$ = Transport time delay (sec)

Rearranging terms and expanding equation (D 1) in a Taylor series

$$T_{Ho}(t) = T_{Hi_p}(t) + \tau_3 \frac{dT_{Hip}(t)}{dt} + \frac{\tau_3}{2!} \frac{d^2T_{Hip}(t)}{dt} + \ldots \qquad \text{(D 2)}$$

For slow temperature changes, the second order and higher terms in equation (D 2) may be ignored.

$$T_{H_{ip}}(t) + \tau_3 \frac{dT_{H_{ip}}(t)}{dt} = T_{Ho}(t) \qquad \text{(D 3)}$$

Let

$$T_{Hi}(t) = T_{Hi_{po}} + \delta T_{H_{ip}}(t) \qquad \text{(D 4)}$$

$$T_{Ho}(t) = T_{H_{o_o}} + \delta T_{Ho}(t)$$

where the lowest zero subscript denotes a steady state value and the delta prefix a small perturbation about this value.

From substitution of equations (D 4) into equation (D 3) and for the temperatures in a steady state at $t \lesssim 0$

$$T_{Hi_{po}} = T_{Ho_o} \tag{D 5}$$

and

$$\delta T_{Hi_p}(t) = \delta T_{Ho}(t) = 0 \tag{D 6}$$

Impose the perturbations at t=0. Substituting equations (D 4) and (D 5) into equation (D 3) with the initial conditions given in equation (D 6)

$$\delta T_{Hi_p}(t) + \tau_3 \frac{d}{dt} \delta T_{Hi_p}(t) = \delta T_{H_o}(t) \tag{D 7}$$

Taking the Laplace transform of equation (D 7) and solving for $\delta T_{Hi} / \delta T_{Ho}$

$$\frac{\delta T_{Hi_p}(s)}{\delta T_{Ho}(s)} = \frac{1}{1 + \tau_3 s}$$

This is equation (39) on page 36.

By following a similar development, the transport delay between a perturbation in the heat exchanger coolant outlet temperature and the resulting perturbation in the reactor inlet plenum coolant temperature can be expressed by the transfer function

$$\frac{\delta T_{Ci_p}(s)}{\delta T_{C_o}(s)} = \frac{1}{1 + \tau_4 s}$$

where δT_{Ci_p} = Reactor inlet plenum coolant temperature perturbation (°F)

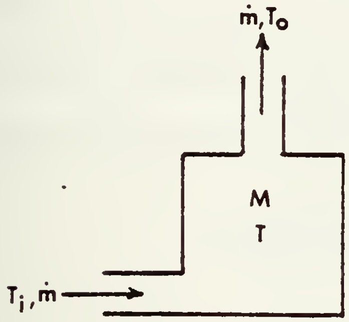
δT_{Co} = Heat exchanger coolant outlet temperature perturbation (°F)

τ_4 = Transport time delay (sec)

This is equation (40) on page

2. Mixing Delay Transfer Function

Let the reactor and heat exchanger coolant inlet plenums be represented by the control volume shown in Figure D-1.



M = Mass of coolant in plenum (lbm/sec)
T = Average plenum coolant temperature (°F)
T_i = Plenum inlet coolant temperature (°F)
T_o = Plenum outlet coolant temperature (°F)
m = Coolant mass flow rate (lbm/sec)

Figure D-1. Mixing Volume

If perfect mixing is assumed, the coolant outlet temperature is equal to the average coolant temperature in the plenum. At heat balance on the volume requires that the net heat flowing into the plenum be equal to the increase in stored energy. Assuming no ambient heat losses, and assuming the temperature of the plenum structural material remains constant, the heat balance per unit time over a time interval Δt is

$$\dot{m}\Delta t C\left[T_i(t) - T_o(t)\right] = MC\frac{dT(t)}{dt}\Delta t = \dot{m}\Delta t C\frac{dT_o(t)}{dt}$$

where C = specific heat of coolant

The resulting equation is

$$\frac{M}{\dot{m}}\frac{dT_o(t)}{dt} + T_o(t) = \tau\frac{dT_o(t)}{dt} + T_o(t) = T_i(t) \qquad \text{(D 8)}$$

where $T = \frac{M}{\dot{m}}$ = mixing time delay.

Let

$$T_i(t) = T_{io} + \delta T_i(t)$$
$$T_o(t) = To_o + \delta T_o(t) \qquad \text{(D 9)}$$

where the lowest zero subscript denotes an initial steady state value and the delta prefix a small perturbation about this value.

Substituting equations (D 8) into equation (D 9)

$$\tau \frac{d}{dt} \delta To(t) + \delta To(t) = \delta T_i(t) \qquad \text{(D10)}$$

Taking the Laplace transform of equation (D10) and solving for $\delta T_o / \delta T_i$

$$\frac{\delta T_o(s)}{\delta T_i(s)} = \frac{1}{1+\tau s}$$

This is equation (41) on page 37.

APPENDIX E

INTERACTIVE PROGRAM LISTING

```
      INTEGER T                                                         INA00010
      DIMENSION X(3000),TIME(3000),TIMEH(3000),LAB1(29),LAB2(21),       INA00020
     $LAB3(10)                                                          INA00030
C     GRAPH TITLE: P O S T   S H U T D O W N   X E N O                  INA00040
      DATA LAB1 / 80,79,83,84,32,83,72,85,84,68,79,87,78,32,88,69,78,79,INA00050
C      N   T R A N S I E N T                                            INA00060
     *78,32,84,82,65,78,83,73,69,78,84 /                                INA00070
C     SCALE TITLE: X E N O N   1 3 5   A T O M S / C M                  INA00080
      DATA LAB2 / 88,69,78,79,78,32,49,51,53,32,65,84,79,77,83,47,67,77,INA00090
C     3                                                                 INA00100
     *51 /                                                              INA00110
C     SCALE TITLE: T I M E   ( H R S )                                  INA00120
      DATA LAB3 / 84,73,77,69,32,40,72,82,83,41 /                       INA00130
C                                                                       INA00140
C     INITIALIZE FOLLOWING PLANT PARAMETERS:                            INA00150
C        U235      URANIUM-235 NUMBER DENSITY (ATOMS/CM3)               INA00160
C        SIGMAA    URANIUM-235 MICROSCOPIC ABSORPTION CROSS SECTION (CM2)INA00170
C        SIGMAF"    URANIUM-235 MICROSCOPIC FISSION CROSS SECTION (CM2) INA00180
C        SIGMAX    XENON-135 MICROSCOPIC ABSORPTION CROSS SECTION (CM2) INA00190
C        GAMMAI    EFFECTIVE FISSION YIELD OF IODINE-135 (%)            INA00200
C        GAMMAX    EFFECTIVE FISSION YIELD OF XENON-135 (%)             INA00210
C        LAMDAI    IODINE-135 DECAY CONSTANT (1/SEC)                    INA00220
C        LAMDAX    XENON-135 DECAY CONSTANT (1/SEC)                     INA00230
C        MDOTM     REACTOR COOLANT MASS FLOW RATE (LBM/SEC)             INA00240
C        CPM       REACTOR COOLANT SPECFIFC THERMAL CAPACITY (BTU/LBM F) INA00250
C        HTM       STEAM FENERATOR TOTAL EFFECTIVE HEAT TRANSFER        INA00260
C                  COEFFICIENT (BTU/SEC F)                              INA00270
C                                                                       INA00280
      REAL IO,K1,LAMDAI/2.875E-5/,LAMDAX/2.0917E-5/,MDOTM/6280./,LOADO, INA00290
     1LOADOM,LOADF                                                      INA00300
      U235 = 6.07E+15                                                   INA00310
      SIGMAA = 393.E-24                                                 INA00320
      SIGMAF = 334.E-24                                                 INA00330
      SIGMAX = 1.5626E-18                                               INA00340
      GAMMAI = 0.06386                                                  INA00350
      GAMMAX = 0.00228                                                  INA00360
      CPM = 1.16                                                        INA00370
      HTM = 5919.                                                       INA00380
C                                                                       INA00560
C     PRINT PROGRAM INTRODUCTION                                        INA00390
      WRITE(5,6000)                                                     INA00400
C                                                                       INA00530
C     READ INITIAL STEADY STATE POWER LEVEL (PWRO)                      INA00570
15    WRITE (6,6002)                                                    INA00580
      READ (5,5000) PWRO                                                INA00590
```

```
C                                                                       INA00600
C     DETERMINE IF INCORRECT DATA ENTERED                               INA00610
      IF ( PWRO .GE. 10.  .AND.  PWRO .LE. 100. ) GO TO 20              INA00620
C        PRINT NOTICE OF INCORRECT DATA ENTRY                           INA00630
         WRITE (6,6200)                                                 INA00640
         GO TO 15                                                       INA00650
C                                                                       INA00660
C     TRANSFER PWRO TO INITIAL DATA FILE                                INA00670
20    WRITE (1,1000) PWRO                                               INA00680
C                                                                       INA00690
C     CALCULATE FOLLOWING INITIAL STEADY STATE PARAMETERS:              INA00700
C        PWROM   INITIAL REACTOR POWER (MWT)                            INA00710
C        FLUXO   INITIAL ONE GROUP NEUTRON FLUX LEVEL (NEUTONS/CM2 SEC) INA00720
C        XO      INITIAL XENON-135 CONCENTRATION (ATOMS/CM3)            INA00730
C        RHOXO   INITIAL XENON-135 REACTIVITY (DELTA K)                 INA00740
C        TMRO    INITIAL AVERAGE REACTOR COOLANT TEMPERATURE (F)        INA00750
C        TFO     INITIAL FUEL TEMPERATURE (F)                           INA00760
C        THOO    INITIAL REACTOR COOLANT OUTLET TEMPERATURE (F)         INA00770
C        TCIO    INITIAL REACTOR COOLANT INLET TEMPERATURE (F)          INA00780
C        THIO    INITIAL STEAM GENERATOR COOLANT INLET TEMPERATURE (F)  INA00790
C        TCOO    INITIAL STEAM GENERATOR COOLANT OUTLET TEMPERATURE (F) INA00800
C        TSO     INITIAL STEAM TEMPERATURE (F)                          INA00810
C        PSO     INITIAL STEAM PRESSURE (PSIA)                          INA00820
C        LOADO   INITIAL TURBINE LOAD (%)                               INA00830
C        LOADOM  INITIAL TURBINE LOAD (MWE)                             INA00840
C                                                                       INA00850
      PWROM = PWRO * 2.31                                               INA00860
      FLUXO = 2.E+12 * PWRO                                             INA00870
      XO = (GAMMAI+GAMMAX)*U235*SIGMAF*FLUXO / (LAMDAX+SIGMAX*FLUXO)    INA00880
      TMRO = 523.                                                       INA00890
      TFO = TMRO + 3.77 * PWRO                                          INA00900
      THOO = TMRO + .15 * PWRO                                          INA00910
      TCIO = TMRO - .15 * PWRO                                          INA00920
      THIO = THOO                                                       INA00930
      TCOO = TCIO                                                       INA00940
      K1 = 2.*MDOTM*CPM/HTM                                             INA00950
      TSO = ( THIO*(1.-K1) + TCOO*(1.+K1) ) *0.5                        INA00960
      PSO = EXP ((ALOG(TSO)-4.77123)/0.22151)                           INA00970
      LOADO = PWRO                                                      INA00980
      LOADOM = LOADO * .68                                              INA00990
C                                                                       INA01070
C     PRINT INITIAL STEADY STATE PARAMETERS                             INA01000
      WRITE(5,6301) PWRO,PWROM,FLUXO,XO,TFO,TMRO,THOO,TCIO,TSO,PSO,LOADOINA01010
     $,LOADOM                                                           INA01020
```

```
C                                                                       INA01030
C     DETERMINE DESIRED SIMULATION                                      INA01040
25    WRITE (6,6003)                                                    INA01050
      READ (5,5000) ANSWER                                              INA01060
C     DETERMINE IF INCORRECT DATA ENTERED                               INA01080
      IANS = IFIX(ANSWER)                                               INA01090
      IF ( IANS .EQ. 1 ) GO TO 30                                       INA01100
         IF ( IANS .EQ. 2 ) GO TO 80                                    INA01110
C           PRINT NOTICE OF INCORRECT DATA ENTRY                        INA01120
            WRITE (6,6200)                                              INA01130
            GO TO 25                                                    INA01140
C                                                                       INA01150
C     DETERMINE INITIAL REACTIVITY CHANGE MECHANISM                     INA01160
30    WRITE (6,6004)                                                    INA01170
      READ (5,5000) ANSWER                                              INA01180
C                                                                       INA01190
C     DETERMINE IF INCORRECT DATA ENTERED                               INA01200
      IANS = IFIX(ANSWER)                                               INA01210
      IF ( IANS .EQ. 1 ) GO TO 35                                       INA01220
         IF ( ANSWER .EQ. 2 ) GO TO 65                                  INA01230
C           PRINT NOTICE OF INCORRECT DATA ENTRY                        INA01240
            WRITE (6,6200)                                              INA01250
            GO TO 30                                                    INA01260
C                                                                       INA01270
C     READ TIME LENGTH (SEC) OF BANK CONTROL ROD MOVEMENT (TSHIM)       INA01280
35    WRITE (6,6005)                                                    INA01300
      READ (5,5000) TSHIM                                               INA01310
C                                                                       INA01320
C     DETERMINE IF INCORRECT DATA ENTERED                               INA01330
      IF ( TSHIM .GE. 0.  .AND. TSHIM .LE. 10. ) GO TO 40               INA01340
C        PRINT NOTICE OF INCORRECT DATA ENTRY                           INA01350
         WRITE (6,6200)                                                 INA01360
         GO TO 35                                                       INA01370
C                                                                       INA01380
C     TRANSFER TSHIM TO INITIAL DATA FILE                               INA01390
40    WRITE (1,1000) TSHIM                                              INA01400
C                                                                       INA01410
C     DETERMINE THE DIRECTION OF BANK CONTROL ROD MOVEMENT (DSHIM)      INA01420
45    WRITE (6,6006)                                                    INA01430
      READ (5,5000) SHIM                                                INA01440
C                                                                       INA01450
C     DETERMINE IF INCORRECT DATA ENTERED                               INA01460
      ISHIM = IFIX(SHIM)                                                INA01470
      IF ( ISHIM .EQ. 1 ) GO TO 55                                      INA01480
         IF ( SHIM .EQ. 2 ) GO TO 50                                    INA01490
C           PRINT NOTICE OF INCORRECT DATA ENTRY                        INA01500
            WRITE (6,6200)                                              INA01510
            GO TO 45                                                    INA01520
```

```
C                                                                        INA01530
C     SET SHIM DIRECTION TO INSERT POSITIVE REACTIVITY ("OUT")           INA01540
50    DSHIM = 1.                                                         INA01550
      GO TO 60                                                           INA01560
C     SET SHIM DIRECTION TO INSERT NEGATIVE REACTIVITY ("IN")            INA01570
55    DSHIM = -1.                                                        INA01580
C                                                                        INA01590
C     TRANSFER DSHIM TO INITIAL DATA FILE                                INA01600
60    WRITE (1,1000) DSHIM                                               INA01610
C                                                                        INA01620
C     SET FINAL TURBINE LOAD = INITIAL TURBINE LOAD                      INA01630
      LOADF = LOADO                                                      INA01640
C                                                                        INA01650
C     TRANSFER LOADF TO INITIAL DATA FILE                                INA01660
      WRITE (1,1000) LOADF                                               INA01670
      GO TO 200                                                          INA01680
C                                                                        INA01690
C     SET THE TIME LENGTH (TSHIM) AMD DIRECTION (DSHIM) OF BANK CONTROL INA01700
C     ROD MOVEMENT = 0                                                   INA01710
65    TSHIM = 0.                                                         INA01720
      DSIM = 0.                                                          INA01730
C                                                                        INA01740
C     TRANSFER TSHIM AND DSHIM TO THE INITIAL DATA FILE                  INA01750
      WRITE (1,1000) TSHIM                                               INA01760
      WRITE (1,1000) DSHIM                                               INA01770
C                                                                        INA01780
C     READ FINAL TURBINE LOAD (LOADF)                                    INA01790
70    WRITE (6,6007)                                                     INA01800
      READ (5,5000) LOADF                                                INA01810
C                                                                        INA01820
C     DETERMINE IF INCORRECT DATA ENTERED                                INA01830
      IF ( LOADF .GE. 10.  .AND.  LOADF .LE. 100. ) GO TO 75             INA01840
C        PRINT NOTICE OF INCORRECT DATA ENTRY                            INA01850
         WRITE (6,6200)                                                  INA01860
         GO TO 70                                                        INA01870
C                                                                        INA01880
C     TRANSFER LOADF TO INITIAL DATA FILE                                INA01890
75    WRITE (1,1000) LOADF                                               INA01900
      GO TO 200                                                          INA01910
C                                                                        INA01920
C     POST SHUTDOWN XENON TRANSIENT ALGORITHM                            INA01930
80    CONTINUE                                                           INA01940
C     CALCULATE EQUILIBRIUM IODINE-135 AT TIME OF SHUTDOWN               INA01950
      IO = GAMMAI * U235 * SIGMAF * FLUXO / LAMDAI                       INA01960
C        CONVERT LAMDAI AND LAMDAX TO 1/MIN(                             INA01980
         LAMDAI = LAMDAI * 60.                                           INA01990
         LAMDAX = LAMDAX * 60.                                           INA02000
```

```
C     CALCULATE INSTANTANEOUS XENON-135 CONCENTRATION                   INA01970
      DO 85 T=1,3000,1                                                  INA02010
         TIME(T) = FLOAT(T-1)                                           INA02020
         X1 = X0 * EXP(-LAMDAX*TIME(T))                                 INA02030
         X2 = LAMDAI * IO/(LAMDAI-LAMDAX)                               INA02040
         X3 = EXP(-LAMDAX*TIME(T)) - EXP(-LAMDAI*TIME(T))               INA02050
C        CONVERT TIME TO HOURS                                          INA02060
         TIME(T) = TIME(T)/60.                                          INA02070
85       X(T) = X1 + X2 * X3                                            INA02080
C     DETERMINE IF THERE IS A POST SHUTDOWN XENON PEAK                  INA02090
      TMAX1 = 1/(LAMDAI-LAMDAX)                                         INA02100
      TMAX2 = LAMDAI/LAMDAX                                             INA02110
      TMAX3 = 1. + (1.-1./TMAX2)*X0/IO                                  INA02120
      TMAX = TMAX1 * ALOG(TMAX2/TMAX3)                                  INA02130
      TMAX = TMAX/60.                                                   INA02140
      IF (TMAX) 95,95,90                                                INA02150
C     CALCULATE THE PEAK XENON CONCENTRATION                            INA02160
90    XMAX1 = X0 * EXP(-LAMDAX*TMAX)                                    INA02170
      XMAX2 = LAMDAI * IO/(LAMDAI-LAMDAX)                               INA02180
      XMAX3 = EXP(-LAMDAX*TMAX) - EXP(-LAMDAI*TMAX)                     INA02190
      XMAX = XMAX1 + XMAX2 * XMAX3                                      INA02200
      GO TO 100                                                         INA02210
95    XMAX = X0                                                         INA02220
      TMAX = 0.0                                                        INA02230
C     CALCULATE THE PEAK XENON REACTIVITY                               INA02240
100   ALPHAX = -SIGMAX/(1.25*U235*SIGMAA)                               INA02250
      RHOMAX = XMAX * ALPHAX                                            INA02260
C                                                                       INA02270
C     TECHTRONIX 4012 GRAPHICS ALGORITHM                                INA02280
      L1 = 29                                                           INA02290
      L2 = 21                                                           INA02300
      L3 = 10                                                           INA02310
      CALL INITT(120)                                                   INA02320
      CALL BINITT                                                       INA02330
      CALL NPTS(3000)                                                   INA02340
      CALL SLIMX(100,970)                                               INA02350
      CALL SLIMY(175,665)                                               INA02360
      CALL CHECK(TIME,X)                                                INA02370
      CALL DSPLAY(TIME,X)                                               INA02380
      CALL NOTATE(325,695,L1,LAB1)                                      INA02390
      CALL DCURSR(65,50,710)                                            INA02400
      CALL MOVABS(50,710)                                               INA02410
      CALL VLABEL(L2,LAB2)                                              INA02420
      CALL NOTATE(465,100,L3,LAB3)                                      INA02430
      CALL XZERO(0)                                                     INA02440
      CALL YZERO(1)                                                     INA02450
      CALL FINITT(70,72)                                                INA02460
C                                                                       INA02470
```

```
C     PRINT PRE-SHUTDOWN REACTOR POWER AND THE TIME, CONCENTRATION, AND INA02480
C     REACTIVITY OF MAXIUM XENON                                        INA02490
      WRITE (6,6400) PWRO,TMAX,XMAX,RHOMAX                              INA02500
      GO TO 300                                                         INA02510
C                                                                       INA02520
C     PRINT INTIAL REACTIVITY CHANGE PARAMETERS                         INA02530
200   WRITE (6,6401) PWRO,TSHIM,DSHIM,LOADF                             INA02540
C                                                                       INA02550
C     NOTIFY USER INPUTS HAVE BEEN ENTERED IN THE SIMULATION PROGRAM ANDINA02560
C     SENT TO THE BATCH SYSTEM FOR EXECUTION.                           INA02570
      WRITE(5,6500)                                                     INA02580
C                                                                       INA02590
300   CONTINUE                                                          INA02600
C                                                                       INA02610
1000  FORMAT(F68.2)                                                     INA02620
5000  FORMAT(F68.2)                                                     INA02630
6000  FORMAT(' ',///,'     THIS IS AN INTERACTIVE PROGRAM WHICH SIMULATEINA02640
     $S THE THERMAL RESPONSE',/,' OF A 231 MWT (68 MWE), HIGHLY ENRICHEDINA02650
     $ PRESSURIZED WATER REACTOR (PWR),',/,' POWER PLANT TO CHANGES IN RINA02660
     $EACTIVITY INITIATED BY CHANGES IN BANK CON-',/,' TROL ROD POSITIONINA02670
     $ OR TURBINE LOAD.  THE REACTIVITY FEEDBACK EFFECTS',/,' RESULTING INA02680
     $FROM CHANGES IN MODERATOR TEMPERATURE AND XENON-135 CONCENTRA-',/,INA02690
     $' TION ARE INCORPORATED INTO THE MODEL.',///,' PLEASE ANSWER THE FINA02700
     $OLLOWING STATEMENTS BY ENTERING THE NUMBER (INCLUDING',/,' THE DECINA02710
     $IMAL POINT, BUT NOT THE PERCENT SYMBOL) WHICH CORRESPONDS TO THE',INA02720
     $/,' DESIRED CHOICE OR VALUE WITHIN THE GIVEN RANGE.',///)         INA02730
6002  FORMAT(' ',///,' ENTER AN INITIAL STEADY STATE POWER LEVEL BETWEENINA02760
     $ 10. AND 100. PERCENT.',/,' NOTE: A MINIMUM OF 10% POWER IS REQUIRINA02770
     $ED TO OPERATE THE REACTOR COOLANT',/,'      PUMPS AND OTHER PLANTINA02780
     $ AUXILIARIES')                                                    INA02790
6003  FORMAT(' ',///,' ENTER THE DESIRED SIMULATION:',/,5X,'1.  MODERATOINA02800
     $R TEMPERATURE AND XENON FEEDBACK AT POWER',/,5X,'2.  POST SHUTDOWNINA02810
     $ XENON BEHAVIOR')                                                 INA02820
6004  FORMAT(' ',///,' ENTER THE INITIAL REACTIVITY CHANGE MECHANISM:',/INA02830
     $,5X,'1.  BANK CONTROL ROD CHANGE',/,5X,'2.  TURBINE LOAD CHANGE') INA02840
6005  FORMAT(' ',///,' ENTER THE TIME LENGTH (SEC) OF BANK CONTROL ROD MINA02850
     $OVEMENT (TSHIM)',/,' NOTE: BANK CONTROL ROD REACTIVITY INSERTION RINA02860
     $ATE IS 1.25E-4 DELTA K/SEC,',/,7X,'DO NOT EXCEED A TOTAL REACTIVITINA02870
     $Y INSERTION OF 35.0E-4 DELTA K',/,7X,'(I.E. A 28 SEC SHIM)')      INA02880
6006  FORMAT(' ',///,' ENTER THE DIRECTION OF BANK CONTROL ROD SHIM:',/,INA02890
     $5X,'1.  IN (NEGATIVE REACTIVITY INSERTION)',/,5X,'2.  OUT (POSITIVINA02900
     $E REACTIVITY INSERTION)')                                         INA02910
6007  FORMAT(' ',///,' ENTER FINAL TURBINE LOAD BETWEEN 10. AND 100. PERINA02920
     $CENT',/,' NOTE: LOAD VARIATION WILL OCCUR AT A FIXED RATE OF 0.5%/INA02930
     $SEC')                                                             INA02940
6200  FORMAT(' ',/,' INCORRECT DATA ENTERED',/)                         INA02960
```

```
6301  FORMAT(' ',/,' INITIAL STEADY STATE PARAMETERS:',/,5X,'REACTOR POWINA02970
     $ER=',F5.2,'%',1X,F6.2,' MWE',/,5X,'THERMAL NEUTRON FLUX=',E9.2,' NINA02980
     $EUTRONS/CM2 SEC',/,5X,'XENON-135 CONCENTRATION=',E9.2,' ATOMS/CM3'INA02990
     $,/,5X,'FUEL TEMPERATURE=',F6.2,' F',/,5X,'AVERAGE REACTOR COOLANT INA03000
     $MODERATOR) TEMPERATURE=',F5.2,' F',/,5X,'REACTOR COOLANT OUTLET TEINA03010
     $MPERATURE=',F6.2,' F',/,5X,'REACTOR COOLANT INLET TEMPERATURE=',F6INA03020
     $.2,' F',/,5X,'SATURATED STEAM TEMPERATURE=',F6.2,' F',/,5X,'SATURAINA03030
     $TED STEAM PRESSURE=',F6.2,' PSIA',/,5X,'TURBINE LOAD=',F6.2,'%',F6INA03040
     $.2,' MWE')                                                        INA03050
6400  FORMAT(' ',4X,'PRE-SHUTDOWN POWER = ',F6.2,'%',/,10X,'PEAK XENON TINA03060
     $IME = ',F6.2,' HRS',/,10X,'PEAK XENON LEVEL = ',E9.3,' ATOMS/CM3',INA03070
     $/,10X,'PEAK XENON REACTIVITY = ',E8.3,' DELTA K')                 INA03080
6401  FORMAT(' ',///,' INITIAL REACTIVITY CHANGE PARAMETERS:',/,5X,'REACINA03090
     $TOR POWER = ',F6.2,' %',/,5X,'SHIM TIME = ',F6.2,' SEC',/,5X,'SHIMINA03100
     $ DIRECTION = ',F6.2,' (1="OUT", -1="IN")',/,5X,'FINAL TURBINE LOADINA03110
     $ = ',F5.2,'%')                                                    INA03120
6500  FORMAT(' ',///,' INPUTS HAVE BEEN ENTERED INTO THE SIMULATION PROGINA03130
     $RAM WHICH HAS BEEN SEN',/,'T TO THE BATCH SYSTEM FOR EXECUTION')  INA03140
      STOP                                                              INA03150
      END                                                               INA03160
```

SIMULATION PROGRAM LISTING

```
//REACTOR1 JOB (1085,1077,WT83),'HEATH,G.G. SMC1639',TIME=90
//  EXEC  CSMPXV
//FT13F001 DD SPACE=(CYL,(5,2))
//X.SYSPRINT  DD  DUMMY
//X.COMPRINT  DD  DUMMY
//X.SYSIN  DD  *
*
*****************************************************************************
*                                                                           *
*  THIS PROGRAM SIMULATES A HIGHLY ENRICHED PRESSURIZED WATER REACTOR.    *
*  THE APPLICABLE PLANT PARAMETERS FROM THE SHIPPINGPORT ATOMIC POWER     *
*  STATION ARE USED IN THE MODEL.  THE THERMAL RESPONSE OF THE PLANT      *
*  TO NORMAL OPERATING TRANSIENTS, INDUCED BY EITHER CONTROL ROD OR       *
*  TURBINE LOAD CHANGES, ARE SIMULATED.  THE PROGRAM ALSO INCORPORATES    *
*  A ROD CONTROL, REACTOR PROTECTION, AND AUTOMATIC AVERAGE REACTOR       *
*  COOLANT TEMPERATURE CONTROL SYSTEM.                                    *
*                                                                           *
*****************************************************************************



*
*
    FIXED SDFLAG,CFLAG1,CFLAGZ,CFLAG3,CFLAG4,THFLAG,TFLAG,SFLAG1,SFLAG2
    FIXED T,T1,T2
*
INITIAL
*
*   ZERO COUNTERS (T1,T2) FOR THE AVERAGE REACTOR COOLANT TEMPERATURE
*   (TMRT) CONTROL ALGORITHM:
*                                  AND
*   ZERO THE FOLLOWING FLAGS (INDICATORS) FOR THE REACTOR PROTECTIOM AND
*   TMRT CONTROL ALGORITHMS (THE FUNCTION OF THESE FLAGS WHEN SET IS DE-
*   SCRIBED, WHEN ZEROED THEY ARE NEUTRAL):
*        SDFLAG  PROTECTIVE FULL INSERTION OF CONTROL RODS (SCRAM)
*        CFLAG1  PROTECTIVE INSERTION OF CONTROL RODS (CUTBACK)
*        CFLAG2  SCRAM ON REOCCURING CUTBACK
*        CFLAG3  ZERO CFLAG1
*        CFLAG4  HIGH STARTUP RATE CUTBACK CONDITION
*        THFLAG  HIGH REACTOR COOLANT OUTLET TEMPERATURE ALARM
*        TFLAG   TMRT OUTSIDE NORMAL TEMPERATURE BAND OF +/- 5F
*        SFLAG1  CONTROL ROD MOVEMENT TO RETURN TMRT TO NOT
*        SFLAG2  ZERO SFLAG1
*
    INCON SDFLAG=0,CFLAG1=0,CFLAG2=0,CFLAG3=0,CFLAG4=0,THFLAG=0, . . .
          TFLAG=0,SFLAG1=0,SFLAG2=0,T1=0,T2=0,T=0
```

```
*
*    ESTABLISH STORAGE FOR DYNAMIC SECTION TRANSFER FUNCTION COEFFICEINTS:
     STORAGE C(3),D(3),E(2),F(3),G(2),H(2),I(3)
*
*    ESTABLISH FOLLOWING PLANT CONSTANTS:
*         U235     URANIUM-235 NUMBER DENSITY (ATOMS/CM3)
*         ALPHA    PROMPT NEUTRON LIFETIME (SEC)
*         BETA     EFFECTIVE DELAYED NEUTRON FRACTION (DELTA K)
*         GAMMAI   EFFECTIVE FISSION YIELD OF IODINE-135
*         GAMMAX   EFFECTIVE FISSION YIELD OF XENON-135
*         LAMDA    DELAYED NEUTRON PRECURSOR DECAY CONSTANT (1/SEC)
*         LAMDAI   IODINE-135 EFFECTIVE DECAY CONSTANT (1/SEC)
*         LAMDAX   XENON-135 EFFECTIVE DECAY CONSTANT (1/SEC)
*         RSHIM    BANK CONTROL ROD REACTIVITY INSERTION RATE (DELTAK/SEC)
*         SIGMAA   URANIUM-235 MICROSCOPIC ABSORPTION CROSS SECTION (CM2)
*         SIGMAF   URANIUM-235 MICROSCOPIC FISSION CROSS SECTION (CM2)
*         SIGMAX   XENON-135 MICROSCOPIC ABSORPTION CROSS SECTION (CM2)
*         ALPHAT   TEMPERATURE COEFFICIENT OF REACTIVITY (DELTA K/F)
*         RSHIM    CONTROL ROD MOVEMENT (SHIM) RATE (DELTA K/SEC)
*         CF       TOTAL THERMAL CAPACITY OF REACTOR METAL (BTU/F)
*         CM       TOTAL THERMAL CAPACITY OF COOLANT IN REACTOR (BTU/F)
*         CS       TOTAL THERMAL CAPACITY OF METAL AND SECONDARY WATER IN
*                  STEAM GENERATOR (S/G) (BTU/F)
*         CPM      REACTOR COOLANT SPECIFIC THERMAL CAPACITY (BTU/LBM F)
*         HFM      REACTOR TOTAL HEAT TRANSFER COEFFICIENT (BTU/SEC F)
*         HTM      S/G TOTAL HEAT TRANSFER COEFFICIENT (BTU/SEC F)
*         MDOTM    REACTOR COOLANT MASS FLOW RATE (LBM/SEC)
*         TAU3     HOT LEG COOLANT FLOW TIME DELAY (SEC)
*         TAU4     COLD LEG COOLANT FLOW TIME DELAY (SEC)
*         TAU5     INLET PLENUM TIME DELAY (SEC)
*         RLOAD    TURBINE LOAD CHANGE RATE (.5%/SEC)
*
     CONSTANT  U235=5.07E+16, BETA=77.0E-4, . . .
               GAMMAI=0.06386, GAMMAX=0.00228, . . .
               LAMDAI=2.875E-5, LAMDAX=2.0917E-5, . . .
               SIGMAA=393.E-24, SIGMAF=334.E-24, SIGMAX=1.5626E-18, . . .
               CF=3100.,CM=5800.,CS=7.38E+4,CPM=1.16, . . .
               HFM=581.,HTM=5919.,MDOTM=6280.,TAU3=3.,TAU4=3., . . .
               TAU6=0.75,C1=0.22151,C2=4.77123
     PARAMETER ALPHA=5.64E-5, LAMDA=0.078, ALPHAT=-3.1E-4, . . .
               RSHIM=1.25E-4, TCOI=7.50, ERROR=0.05, DUMMY=0.0
```

```
*
*   CALCULATE REMAINING CONSTANT PLANT PARAMETERS:
          GAMMA = 1./(MDOTM*CPM)
          TAU0 = CM/(MDOTM*CPM)
          TAU1 = CF/HFM
          TAU2 = CM/HFM
          TAU5 = CS/HTM
          K1 = 2. * MDOTM * CPM/HTM
*
  PROCEDURE PWR0,TSHIM,DSHIM,LOADF = READIN(DUMMY)
*   READ INITIAL STEADY STATE POWER LEVEL (PWR0) (%)
    READ (5,5000) PWR0
*
*   READ THE TIME LENGTH OF BANK CONTROL ROD MOVEMENT (TSHIM)
    READ (5,5000) TSHIM
*
*   READ THE DIRECTION OF BANK CONTROL ROD MOVEMENT (DSHIM)
    READ (5,5000) DSHIM
*
*   READ THE FINAL TURBINE LOAD (LOADF) (%)
    READ (5,5000) LOADF
  ENDPROCEDURE
*
*   CALCULATE FOLLOWING INITIAL STEADY STATE PARAMETERS:
*         PWR0T    INITIAL REACTOR POWER (BTU/SEC)
*         FLUX0    INITIAL THERMAL NEUTRON FLUX (NEUTRONS/CM2 SEC)
*         X0       INITIAL EQUILIBRIUM XENON-135 NUMBER DENSITY(ATOMS/CM3)
*         ALPHAX   XENON-135 COEFFIECINET OF REACTIVITY (DELTA K/XE-135)
*         TMR0     INITIAL AVERAGE REACTOR COOLANT TEMPERATURE (F)
*         THO0     INITIAL REACTOR COOLANT OUTLET TEMPERATURE (F)
*         TCOI     INITIAL REACTOR COOLANT INLET TEMPERATURE (F)
*         THI0     INITIAL STEAM GENERATOR COOLANT INLET TEMPERATURE (F)
*         TCO0     INITIAL STEAM GENERATOR COOLANT OUTLET TEMPERATURE (F)
*         LOAD0    INITIAL TURBINE LOAD (%)
*         TS0      INITIAL SATURATED STEAM TEMPERATURE (F)
*         PS0      INITIAL SATURATED STEAM PRESSURE (LBF/IN2)
*         A0       INITIAL TURBINE THROTTLE VALVE SETTING
*
          PWR0T = PWR0 * 2.19E+3
          FLUX0 = 2.E+12 * PWR0
          X0 = (GAMMAX+GAMMAI)*U235*SIGMAF*FLUX0/(LAMDAX+SIGMAX*FLUX0)
          ALPHAX = -1./(X0 + SIGMAA/SIGMAX*U235)
          TMR0 = 523.
          THO0 = TMR0 + .15 * PWR0
          TCI0 = TMR0 - .15 * PWR0
          THI0 = THO0
          TCO0 = TCI0
          LOAD0 = PWR0
```

```
            TSO = ( THIO * (1.-K1) + TCOO * (1.+K1) ) * 0.5
            PSO = EXP((ALOG(TSO)-C2)/C1)
            AO = LOADO/100.
*
  NOSORT
*
*   CALCULATE THE TURBINE LOAD CHANGE (LOADC) (%)
    LOADC = LOADO - LOADF
*
*   SET THE DIRECTION OF TURBINE LOAD CHANGE
    IF ( LOADC ) 5,10,15
5       DLOAD = 1.
        GO TO 17
10      DLOAD =0.0
        RLOAD =0.0
        GO TO 20
15      DLOAD = -1.
*
*   CALCULATE THE TURBINE LOAD CHANGE TIME (TLOAD)
17  RLOAD = 0.005
    TLOAD = ABS(LOADC)*2.0
*
*   PRINT INITIAL PLANT PARAMETERS
20  WRITE(6,5000) PWRO,TMRO,THOO,TCIO,TSO,PSO,LOADO,DSHIM,TSHIM,LOADF
*
*   CALCULATE DYNAMIC SECTION TRANSFER FUNCTION (TRANSF) COEFFICIENTS:
*           REACTOR COOLANT OUTLET TEMPERATURE TRANSF COEFFICIENTS:
                C(1) = TAUO/2. * (TAU1/TAU2 + 1.) - TAU1
                C(2) = TAUO * TAU1/2.
                C(3) = -1.
                D(1) = C(1) + 2.*TAU1
                D(2) = C(2)
                D(3) = -C(3)
                G(1) = 0.0
                G(2) = GAMMA
*           XENON TRANSFER FUNCTION COEFFICENTS:
                C3 = SIGMAF*U235
                C4 = SIGMAX*FLUXO
                C5 = SIGMAX*XO
                E(1) = (GAMMAX*C3 - C5)
                E(2) = LAMDAI * (C3*(GAMMAI+GAMMAX) - C5)
                F(1) = C4 + LAMDAI + LAMDAX
                F(2) = 1.
                F(3) = LAMDAI*(C4+LAMDAX)
```

```
*        REACTOR KINETICS TRANSFER FUNCTION COEFFICEINTS
            H(1) = PWRO
            H(2) = LAMDA * PWRO
            I(1) = ALPHA*LAMDA + BETA
            I(2) = ALPHA
            I(3) = 0.0
*
  SORT
*
*   ESTABLISH INITIAL ROD AND TURBINE CONTROL TIMES:
         TIME1 = 0.0
         TIME2 = TSHIM
         SLOAD = 0.0
*
*   MAJOR PLANT PARAMETERS USED IN DYNAMIC SECTION:
*        POWER    INSTANTANEOUS REACTOR POWER (%)
*        PWRO     INITIAL STEADY STATE REACTOR POWER LEVEL (%)
*        PWR      REACTOR POWER PERTURBATION (%)
*        PWRT     REACTOR POWER PERTURBATION (BTU/SEC)
*        SUR      REACTOR POWER STARTUP RATE (DECADES/MIN)
*        FLUX     THERMAL NEUTRON FLUX PERTURBATTION (NEUTRONS/CM2 SEC)
*        RHO      CORE REACTIVITY (DELTA K)
*        RHOE     CONTROL ROD REACTIVITY (DELTA K)
*        RHOT     MODERATOR TEMPERATURE FEEDBACK REACTIVITY (DELTA K)
*        RHOX     XENON-135 FEEDBACK REACTIVITY (DELTA K)
*        ALPHAX   XENON-135 COEFFICIENT OF REACTIVITY (DELTA K/XE-135)
*        XE-135   INSTANTANEOUS XENON-135 NUMBER DENSITY (ATOMS/CM3)
*        XO       INITIAL XENON-135 NUMBER DENSITY (ATOMS/CM3)
*        X        XENON-135 NUMBER DENSTIY PERTURBATION (ATOMS/CM3)
*        ALPHAT   TEMPERATURE COEFFICIENT OF REACTIVITY (DELTA K/F)
*        TAV      INSTANTANEOUS AVERAGE REACTOR COOLANT TEMPERATURE (F)
*        TMRO     INITIAL AVERAGE REACTOR COOLANT TEMPERATURE (F)
*        TMR      AVERAGE REACTOR COOLANT TEMPERATURE PERTURBATION (F)
*        TH       INSTANTANEOUS REACTOR COOLANT OUTLET TEMPERATURE (F)
*        THOO     INITIAL REACTOR COOLANT OUTLET TEMPERATURE (F)
*        THO      REACTOR COOLANT OUTLET TEMPERATURE PERTURBATION (F)
*        THIO     INITIAL STEAM GENERATOR COOLANT INLET TEMPERATURE (F)
*        THI      STEAM GENERATOR INLET TEMPERATURE PERTURBATION (F)
*        TC       INSTANTANEOUS REACTOR COOLANT OUTLET TEMPERATURE (F)
*        THIP     STEAM GENERATOR INLET PLENUM COOLANT TEMPERATURE
                  PERTURBATION (F)
*        TCIO     INITIAL REACTOR COOLANT INLET TEMPERATURE (F)
*        TCI      REACTOR COOLANT INLET TEMPERATURE PERTURBATION (F)
*        TCIP     REACTOR INLET PLENUM COOLANT TEMPERATURE PERTURBATION
*        TCOO     INITIAL STEAM GENERATOR COOLANT OULET TEMPERATURE (F)
*        TCO      STEAM GENERATOR OUTLET TEMPERATURE PERTURBATION (F)
*        PST      INSTANTANEOUS SATURATED STEAM PRESSURE (PSIA)
*        TST      INSTANTANEOUS SATURATED STEAM TEMPERATURE (F)
```

```
*          PWRSG    INSTANTANEOUS POWER DELIVERED TO TURBINE (%)
*          PWRSGT   INSTANTANEOUS POWER DELIVERED TO THE TURBINE (BTU/SEC)
*          A        INSTANTANEOUS TURBINE THROTTLE VALVE SETTING
*
*
DYNAMIC
*
*   REACTOR KINETICS
       RHO = RHOE + RHOT + RHOX
       PWR = TRANSF(2,I,1,H,RHO)
       PWRT = PWR * 2.19E+3
       FLUX = PWR * 2.0E+12
*   MODERATOR TEMPERATURE FEEDBACK
       RHOT = TMR * ALPHAT
       TMR = (THO+TCI)/2.
*   XENON-135 FEEDBACK
       X = TRANSF(2,F,1,E,FLUX)
       RHOX = X * ALPHAX
* REACTOR AND STEAM PLANT ALGORITHM
*   PRIMARY THERMAL LOOP
       THO1 = TRANSF(2,D,1,G,PWRT)
       THO2 = TRANSF(2,D,2,C,TCI)
       THO = THO1 - THO2
       TCIP = REALPL(0.0,TAU4,TCO)
       TCI = REALPL(0.0,TAU6,TCIP)
*   SECONDARY THERMAL LOOP
       THIP = REALPL(0.0,TAU3,THO)
       THI = REALPL(0.0,TAU6,THIP)
       PWRSG = A * 100.0
       LOAD = PWRSG
       PWRSGT = PWRSG * 2.19E+3
  PROCEDURE TCO = LOOP(PWRSGT,PWROT,TCOI,THI,TCI,ERROR,TAU5,K1)
            TCO = IMPL(TCOI,ERROR,FOFTCO)
              SGVARY = (THI+TCO)/2. - (PWRSGT-PWROT)/HTM
              TS = REALPL(0.0,TAU5,SGVARY)
              FOFTCO = (2.*TS - THI*(1.-K1))/(1.+K1)
  ENDPROCEDURE
       TST = TSO + TS
       PST = EXP((ALOG(TST)-C2/C1)
*
*   ROD CONTROL
       RHOE1 = DSHIM * RSHIM * RAMP(TIME1)
       RHOE2 = DSHIM * RSHIM * RAMP(TIME2)
       RHOE = RHOE1 - RHOE2
*   TURBINE THROTTLE CONTROL
       A1 = A0 + DLOAD * RLOAD * RAMP(SLOAD)
       A2 = DLOAD * RLOAD * RAMP(TLOAD)
       A = A1 - A2
```

```
*
  PROCEDURE POWER,XE135,TAV,TH,TC,SUR  = RCS(SDFLAG,CFLAG1,CFLAG2, . . .
            CFLAG3,THFLAG,TFLAG,SFLAG1,SFLAG2,T1,T2,T, . . .
            PWRO,PWR,TMRO,TMR,THOO,THO,TCIO,TCI,XO,X,CFLAG4)
*
*    CHECK IF VALID INTEGRATION STEP PERFORMED
     IF (KEEP .NE. 1) GO TO 115
*    CALCULATE INSTANTEOUS PARAMETERS
        POWER = PWRO + PWR
        TAV = TMRO + TMR
        TH = THOO + THO
        TC = TCIO + TCI
        XE135 = XO + X
*    CALCULATE REACTOR POWER STARTUP RATE (SUR)
        PWRDOT = DERIV(PWRO,POWER)
        SUR = PWRDOT * 0.06
*
*    REACTOR PROTECTION ALGORITHM
     IF (TIME .LE. 0.05) GO TO 115
*    CHECK IF SCRAM IN PROGRESS
     IF (SDFLAG .EQ. 1) GO TO 115
*    CHECK FOR HIGH POWER SCRAM CONDITION (POWER>138%)
     IF (POWER .GT.138.) GO TO 25
*       CHECK FOR HIGH TEMPERATURE SCRAM CONDITION (TH>550F)
        IF(TH .GE. 550.) GO TO 30
*          CHECK IF ANY PREVIOUS CUTBACK HAS CLEARED
           IF (CFLAG3 .EQ. 1) CFLAG1 = 0
*             CHECK IF CUTBACK IN PROGRESS
              IF (CFLAG1 .EQ. 1) GO TO 45
*                CHECK FOR HIGH SUR (>1.74) CUTBACK CONDITION
                 IF (SUR .GE. 1.74) GO TO 60
*                   CHECK FOR HIGH POWER CUTBACK CONDITION (POWER>114%)
                    IF (POWER .GE. 114.) GO TO 65
*                      CHECK IF THOT ALARM EXIST
                       IF (THFLAG .EQ. 1) GO TO 85
*                         CHECK IF THOT ALARM CONDITION EXIS (TH>544F)
                          IF (TH .LE. 544.) GO TO 90
*                            SET THFLAG
                             THFLAG = 1
*                            PRINT NOTICE THOT ALARM
                             WRITE (6,6001) TH,TIME
                             GO TO 90
*
*    PRINT NOTICE HIGH POWER SCRAM
25   WRITE (6,6005) POWER,TIME
     GO TO 40
```

```
*
*     PRINT NOTICE HIGH TEMPERATURE SCRAM
   30 WRITE (6,6006) POWER,TH,TIME
*
*     SET SCRAM PARAMETERS:
*        SET ROD DIRECTION "IN"
   40    DSHIM = -1.
*        SET CONTROL ROD SCRAM INSERTION RATE
         RSHIM = 0.19
*        SET TIME TO START SCRAM
         TIME1 = TIME
*        SET TIME TO STOP SCRAM
         TIME2 = TIME + 1.35
*        TRIP TURBINE THROTTLE
         AO = 0.0
         DLOAD = -1.
         SLOAD = TIME
         TLOAD = TIME + 1.
*        SET SDFLAG
         SDFLAG = 1
         GO TO 115
*
*     CHECK IF HIGH POWER CUTBACK CONDITION CLEARED
   45 IF (CFLAG .EQ. 1) GO TO 50
        IF (POWER .GE. 100.) GO TO 115
*           PRINT NOTICE HIGH POWER CUTBACK CONDITION CLEARED
            WRITE (6,6007) POWER,TIME
            GO TO 55
*
*     CHECK IF HIGH SUR CUTBACK CONDITION CLEARED
   50 IF (SUR .GE. 1.2) GO TO 115
*        PRINT NOTICE HIGH SUR CUTBACK CONDITION CLEARED
         WRITE(6,6008) POWER,SUR,TIME
*
*     STOP CUTBACK
   55    TIME1 = TIME
         TIME2 = TIME
*        SET CFLAG2 (REOCCURING CUTBACK WILL RESULT IN SCRAM)
         CFLAG2 = 1
*        SET CFLAG 3 (ZERO CFLAG1)
         CFLAG3 = 1
         GO TO 115
*
*     PRINT NOTICE HIGH SUR CUTBACK CONDITION
   60 WRITE (6,6009) POWER,SUR,TIME
      CFLAG4 = 1
      GO TO 70
```

```
*
*    PRINT NOTICE HIGH POWER CUTBACK CONDITION
65   WRITE (6,6010) POWER,TIME
*
*    CHECK FOR REOCCURING CUTBACK
70   IF (CFLAG2 .EQ. 1) GO TO 80
*        SET CUTBACK PARAMETERS:
*            SET ROD DIRECTION "IN"
             DSHIM = -1.
*            SET TIME TO START CUTBACK
             TIME1 = TIME
             TIME2 = TIME  + 370.
*            SET CLFAG1
             CFLAG1 = 1
*            TRIP TURBINE THROTTLE TO MID POSITION
             IF ( AO .LE. 0.5) GO TO 75
                 AO = 0.5
75   DLOAD = -1.
     SLOAD = TIME
     TLOAD = TIME  + 1.
     GO TO 115
*
*    PRINT NOTICE REOCCURING CUTBACK RESULTING IN SCRAM
80   WRITE (6,6011) POWER,SUR,TIME
     GO TO 40
*
*    CHECK IF THOT ALARM CONDITION CLEARED
85   IF (TH .GE. 544.) GO TO 90
*        REZERO THFLAG
         THFLAG = 1
*        PRINT NOTICE THOT ALARM CONDITION CLEARED
         WRITE (6,6002) TH,TIME
*
*    AVERAGE REACTOR COOLANT TEMPERATURE (TAV) CONTROL SYSTEM ALGORITHM
*
*    CHECK FOR TMR CONTROL CONDITION
90   IF (TFLAG .EQ. 1) T1=T1+1
*        CHECK IF TMR IS  OUTSIDE NORMAL OPERATING TEMPERATURE (NOT) BAND
         IF ( ABS(TMR) .LE. 5. ) GO TO 110
             T2 = T2 + 1
             IF (TFLAG .EQ. 1) GO TO 95
*                SET TFLAG (TMR OUTSIDE NOT BAND)
                 TFLAG = 1
*                SET TIME WHEN TMR WENT OUTSIDE NOT BAND
                 TIMET = TIME
95   T = T2 - T1
     IF (T .EQ. 1) GO TO 100
```

```
*      REZERO TFLAG
       TFLAG = 0
       GO TO 115
*   CALCULATE THE AMOUNT OF TIME TMR OUTSIDE NOT BAND
100 TIME1 = TIME - TIMET
*   CHECK IF TMR OUTSIDE NOT BAND > 10 MINUTES
    IF (TIME .LT. 600.) GO TO 115
       IF (SFLAG .EQ. 1) GO TO 115
*      PRINT NOTICE OF TMR OUTSIDE NOT BAND > 10 MINUTES
       WRITE (6,6003) TAV,TIME
*      SET TIMES FOR TMR CONTROL SHIM
       TIME1 = TIME
       TIME2 = TIME + 9.E+4
*      SET SFLAG1
       SFLAG = 1
       TIME1 = TIME
*      DETERMINE SHIM DIRECTION REQUIRED TO RETURN TMR TO NOT BAND
       IF (TMR .LT. 0.) GO TO 105
*         SET SHIM DIRECTION "IN"
          DSHIM = -1.
          WRITE (6,6013) TIME1,DSHIM
          GO TO 115
*      SET SHIM DIRECTION "OUT"
105    DSHIM = 1.
       GO TO 115
*   CHECK IF TMR CONTROL SHIM COMPLETED
110 IF (SFLAG2 .EQ. 1) SFLAG1 = 0
*      CHECK IF TMR CONTROL SHIM IN PROGRESS
       IF (SFLAG1 .NE. 1) GO TO 115
*         CHECK IF TMR RETURN TO NOT BAND +/- 2F
          IF ( ABS(TMR) .GT. 2. ) GO TO 115
*            PRINT NOTICE TMR RETURNED TO NOT BAND
             WRITE (6,6004) TAV,TIME
*            STOP TMR CONTROL SHIM
*            SET SFLAG2 (ZERO SFLAG1)
             SFLAG2 = 1
*            SET TIME TO STOP CONTROL SHIM
             TIME1 = TIME
             TIME2 = TIME
*            REZERO TFLAG
             TFLAG = 0
*            ZERO COUNTERS
             T1 = 0
             T2 =0
115 CONTINUE
  ENDPROCEDURE
*
```

```
*
TERMINAL
*
5000  FORMAT(F68.3)
6000  FORMAT(' INITIAL STEADY STATE PARAMETERS:',/,5X,'REACTOR POWER=',F
     $6.2,'%',/,5X,'AVERAGE REACTOR COOLANT TEMPERATURE=',F6.2,' F',/,5X
     $,'REACTOR COOLANT OUTLET TEMPERATURE=',F6.2,' F',/,5X,'REACTOR COO
     $LANT TEMPERATURE=',F6.2,' F',/,5X,'SATURATED STEAM TEMPERATURE=',F
     $6.2,' F',/,5X,'SATURATED STEAM PRESSURE=',F6.2,' PSIA',/,5X,'TURBI
     $NE LOAD=',F6.2,'%',/,' TRANSIENT INPUTS:',/,5X,'SHIM DIRECTION=',F
     $4.0,' (-1="IN", 1="OUT")',/,5X,'SHIM TIME=',F6.2,' SECONDS',/,5X,'
     $FINAL TURBINE LOAD=',F6.2,'%')
6001  FORMAT( 'HIGH REACTOR COOLANT OUTLET TEMPERATURE (THOT) ALARM',/,5
     $X,'THOT=',F6.2,' F',/,5X,'TIME=',F6.2,' SECONDS')
6002  FORMAT(' HIGH REACTOR COOLANT OUTLET TEMPERATURE ALARM CLEARED',/,
     $5X,'THOT=',F6.2,' F',/,5X,'TIME=',F6.2,' SECONDS')
6003  FORMAT(' AVERAGE REACTOR COOLANT TEMPERATURE (TAVE) OUTSIDE NORMAL
     $ OPERATING BAND OF +/- 5F FOR MORE THAN 10 MINUTES',/,5X,'TAVE=',
     $F6.2,' F',/,5X,'TIME=',F9.2,' SECONDS')
6004  FORMAT(' AVERAGE REACTOR COOLANT TEMPERATURE RETURNED TO NORMAL OP
     $ERATING BAND',/,5X,'TAVE=',F6.2,' F',/,5X,'TIME=',F6.2,' SECONDS',
     $/,5X,'AUTOMATIC ROD CONTROL CEASED')
6005  FORMAT(' HIGH POWER SCRAM INITIATED',/,' TURBINE THROTTLE VALVE TR
     $IPPED',/,5X,'REACTOR POWER=',F6.2,'%',/,5X,'TIME=',F6.2,' SECONDS'
     $)
6006  FORMAT(' HIGH TEMPERATURE SCRAM INITIATED',/,' TURBINE THROTTLE VA
     $LVE TRIPPED',/,5X,'REACTOR POWER=',F6.2,'%',/,5X,'REACOTR OUTLET T
     $EMPERATURE=',F6.2,' F',/,5X,'TIME=',F6.2,' SECONDS')
6007  FORMAT(' HIGH POWER CUTBACK CONDITION CLEARED, CUTBACK CEASED',/,5
     $X,'REACTOR POWER=',F6.2,'%',/,5X,'TIME=',F6.2,' SECONDS')
6008  FORMAT(' HIGH STARTUP RATE CUTBACK CONDITION CLEARED, CUTBACK CEAS
     $ED',/,5X,'REACTOR POWER=',F6.2,'%',/,5X,'STARTUP RATE=',E9.5,' DPM
     $',/,5X,'TIME=',F6.2,' SECONDS')
6009  FORMAT(' HIGH STARTUP RATE CUTBACK INITIATED',/,' TURBINE THROTTLE
     $ TRIPPED TO MID POSITION',/,5X,'REACTOR POWER=',F6.2,'%',/,5X,'STA
     $RTUP RATE=',F5.2,' DPM',/,5X,'TIME=',F5.2,' SECONDS')
6010  FORMAT(' HIGH POWER CUTBACK INITIATED',/,' TURBINE THROTTLE VALVE
     $ TRIPPED TO MID POSITION',/,5X,'REACTOR POWER=',F6.2,'%',/,5X,'TIM
     $E=',F6.2,' SECONDS')
6011  FORMAT(' REOCCURRING CUTBACK CONDITION',/,' SCRAM INITIATED',/,' T
     $URBINE THROTTLE VALVE TRIPPED',/,5X,'REACTOR POWER=',F6.2,'%',/,5X
     $,'STARTUP RATE=',F6.2,' DPM',/,5X,'TIME=',F6.2,'SECONDS')
*
TITLE   SIMULATION OF A PRESSURIZED WATER REACTOR
PRINT RHO,RHOE,RHOT,POWER,LOAD,TAV,TH,TC
RANGE RHO,RHOE,RHOT,POWER,LOAD,TAV,TH,TC
*
```

```
LABEL    SIMULATION OF A PRESSURIZED WATER REACTOR
*
OUTPUT TIME,TAV(500.,550.),TH(500.,550.),TC(500.,550.)
LABEL              TEMPERATURE RESPONSE
PAGE HEIGHT = 5, WIDTH = 7
PAGE XYPLOT
*
OUTPUT TIME,POWER(0.0,100.),LOAD(0.0,100.0)
LABEL             POWER AND LOAD RESPONSE
PAGE HEIGHT = 5, WIDTH = 7
PAGE XYPLOT
*
OUTPUT TIME,RHO(-.01,.01),RHOE(-.01,.01),RHOT(-.01,.01)
LABEL               REACTIVITY RESPONSE
PAGE HEIGHT = 5, WIDTH = 7
PAGE XYPLOT
*
TIMER  FINTIM=600., OUTDEL=0.1, PRDEL=5.0
*
END
INPUT
ENDINPUT
RESET
*
TITLE    SIMULATION OF A PRESSURIZED WATER REACTOR
TITLE                XENON TRANSIENT
RANGE RHO,RHOE,RHOT,RHOX,XE135,TAV,POWER,LOAD
PRINT RHO,RHOE,RHOT,RHOX,XE135,TAV,POWER,LOAD
*
LABEL    SIMULATION OF A PRESSURIZED WATER REACTOR
*
OUTPUT TIME,POWER(0.0,100.),LOAD(0.0,100.0)
LABEL             POWER AND LOAD RESPONSE
LABEL                XENON TRANSIENT
PAGE HEIGHT = 5, WIDTH = 7
PAGE XYPLOT
*
OUTPUT TIME,TAV(500.,550.),TH(500.,550.),TC(500.,550.)
LABEL              TEMPERATURE RESPONSE
LABEL                XENON TRANSIENT
PAGE HEIGHT = 5, WIDTH = 7
PAGE XYPLOT
*
OUTPUT TIME,XE135,TAV(500.,550.)
LABEL        XE AND AVG TEMPERATURE RESPONSE
LABEL                XENON TRANSIENT
PAGE HEIGHT = 5, WIDTH = 7
PAGE XYPLOT
```

```
*
OUTPUT TIME,RHO(-.01,.01),RHOE(-.01,.01),RHOT(-.01,.01),RHOX(-.01,.01)
LABEL              REACTIVITY RESPONSE
LABEL                XENON TRANSIENT
PAGE HEIGHT = 5, WIDTH = 7
PAGE XYPLOT
*
TIMER FINTIM=5.4E+3,OUTDEL=1.0,PRDEL=60.0
*
END
INPUT
ENDINPUT
STOP
ENDJOB
```

INTERFACE PROGRAM LISTING

```
&TYPEOUT ERROR
&TYPEOUT ON
VSET RDYMSG OFF
GLOBAL T TEKLIB SYSLIB SSPLIB
CP SET LINELN 80
FILEDEF 01 DSK INITAL DATA
LOAD INTACT FORTRAN
COMBINE PLANT1 CSMP P1 CORE CSMP P1 INITAL DATA P1
COMBINE PLANT2 CSMP P1 PLANT1 CSMP P1 END1 CSMP P1
COMBINE PLANT3 CSMP P1 PLANT2 CSMP P1 INITAL DATA P1
COMBINE PLANT  CSMP P1 PLANT3 CSMP P1 END2 CSMP P1
SUBMIT PLANT CSMP P1
```

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